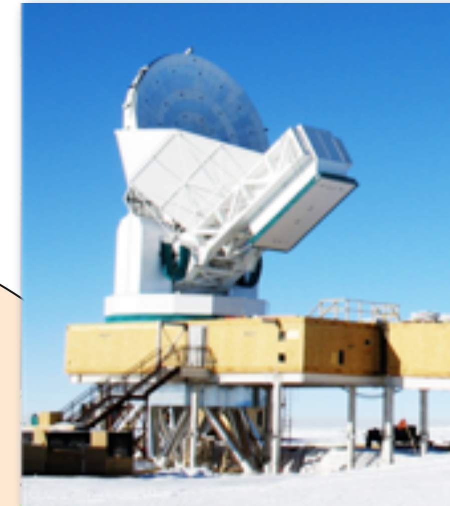
Cosmic Microwave Background (CMB) Thrust

Inflation-era High Energy Physics and neutrino masses via CMB polarization measurements with the South Pole Telescope.

Argonne CMB Detector Development Collaboration between High Energy Physics, the Material Science Division, and the Center for Nanoscale Materials.

And with strong University Partners:
University of Chicago/KICP, U.C.Berkeley & LBL,
U.Colorado at Boulder & NIST, Case Western, U. Michigan,
and McGill University.

HEP provides enabling technology for frontier research - excellent synergy.



TECHNOLOGY

- Superconducting Transition-Edge Sensor (TES) Detectors
- Argonne TES Development Project
- Seeded by LDRD (ANL)

PLATFORM

- South Pole Telescope. Cutting edge instrument & strong collaboration
- PI: John Carlstrom

SPTpol

COSMIC FRONTIER

- Inflation
- Neutrino masses

Exploring the GUT scale through CMB polarization

"*The science of the CMB is therefore also high-energy particle physics... the required large-scale integration and detailed analysis of very large data sets are critical areas of HEP expertise needed to make possible the next great step forward.*" - **PASAG report, 2009**

"*The [CMB] B-modes are a window allowing us to peer far back beyond the screen of the CMB into the period of inflation. The convincing detection of B-mode polarization in the CMB ... would represent a watershed discovery.*" - **A&A Decadal 2010**

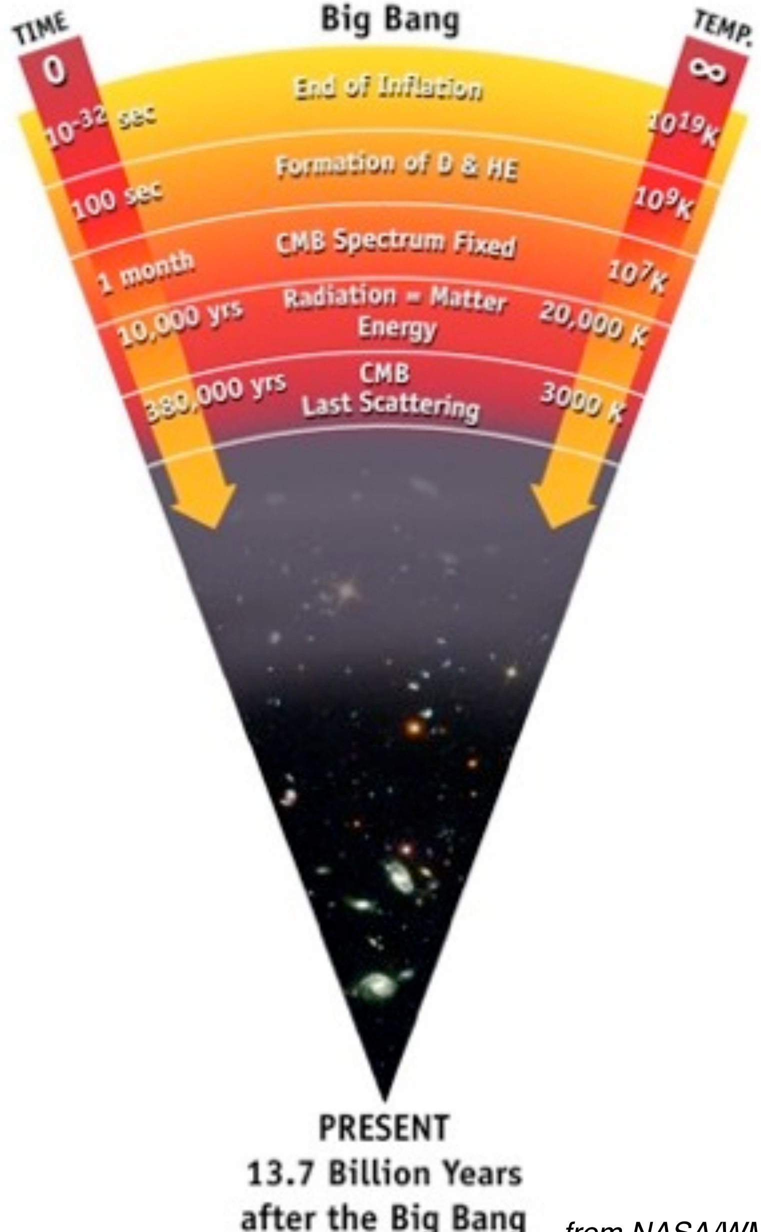
"DOE has been supporting specific technology development activities for JDEM and LSST, as well as more general technology development for TeV experiments and cosmic microwave background polarization experiments. Continuation of these is of great importance to the committee's recommended program." - **A&A Decadal 2010**

Probing the Cosmic Frontier

We now have a model that describes the evolution of our Universe from a hot and dense state.

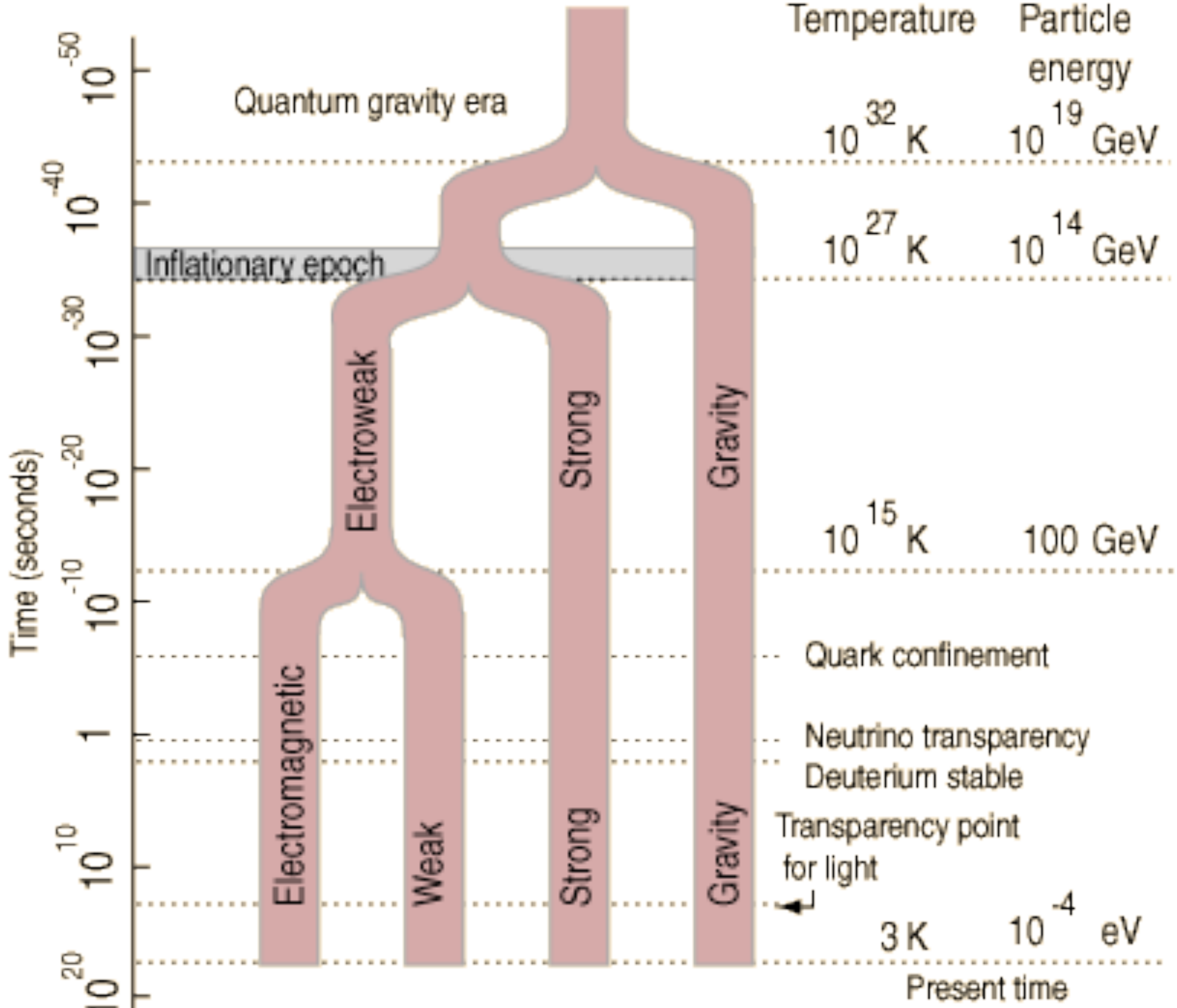
The model has some unusual features ***- new physics -*** Dark Matter, Dark Energy, and starts with a period of Inflation.

Most of the model has been learned from measurements of the cosmic microwave background (CMB).

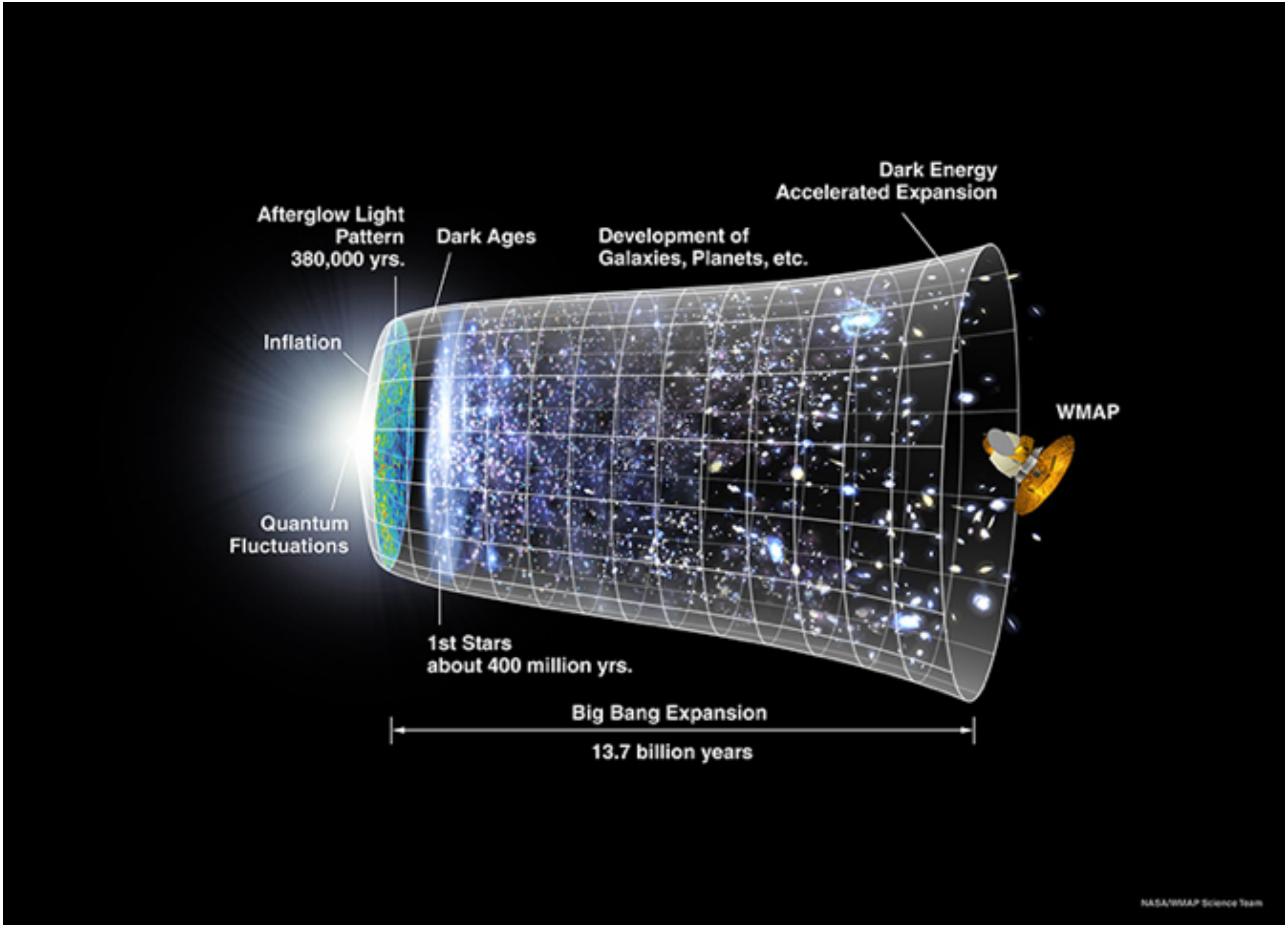


from NASA/WMAP Team

Early universe as an HEP lab



HyperPhysics (©C.R. Nave, 2010)


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Discovery of the Cosmic Microwave Background

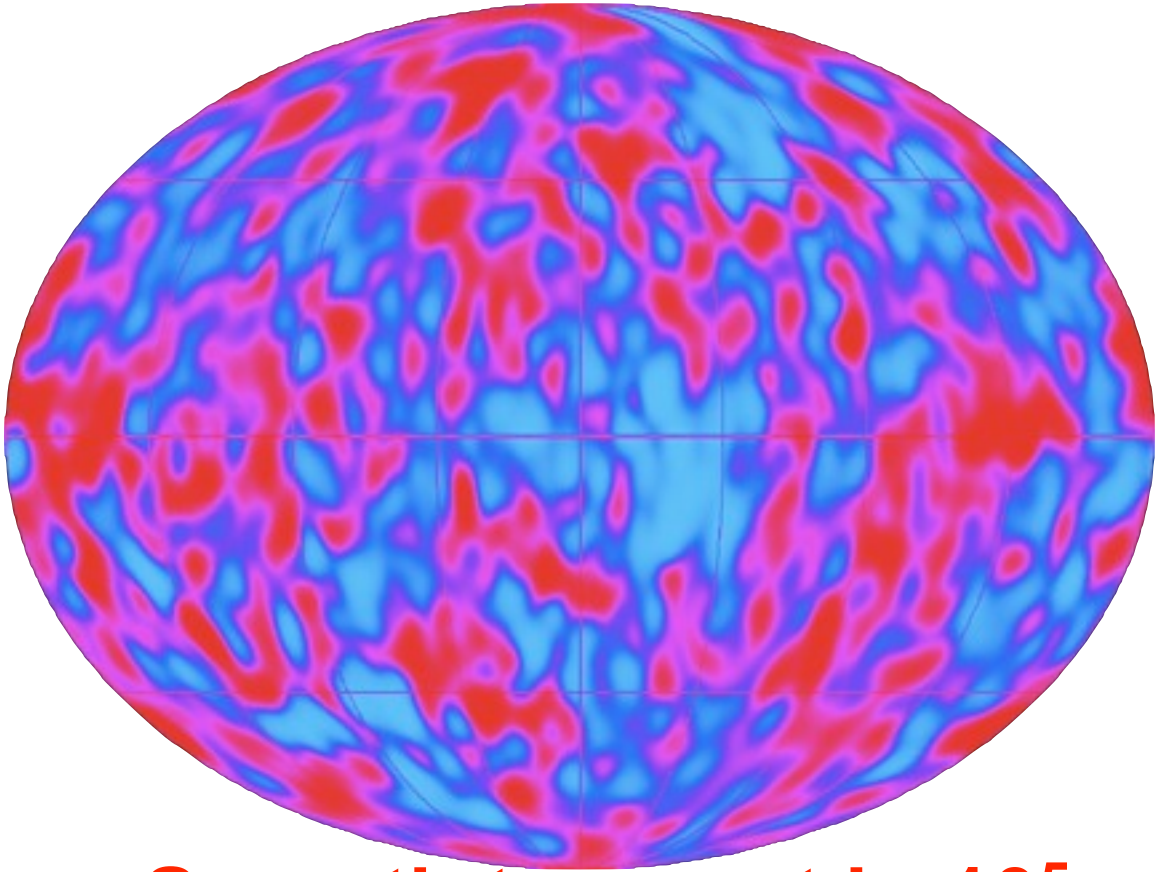
"smoking gun" evidence for the <u>Hot Big Bang</u>

Penzias & Wilson 1965

Received 1978 Nobel Prize

Enormous impact on Cosmology

Structure in background discovered in 1992

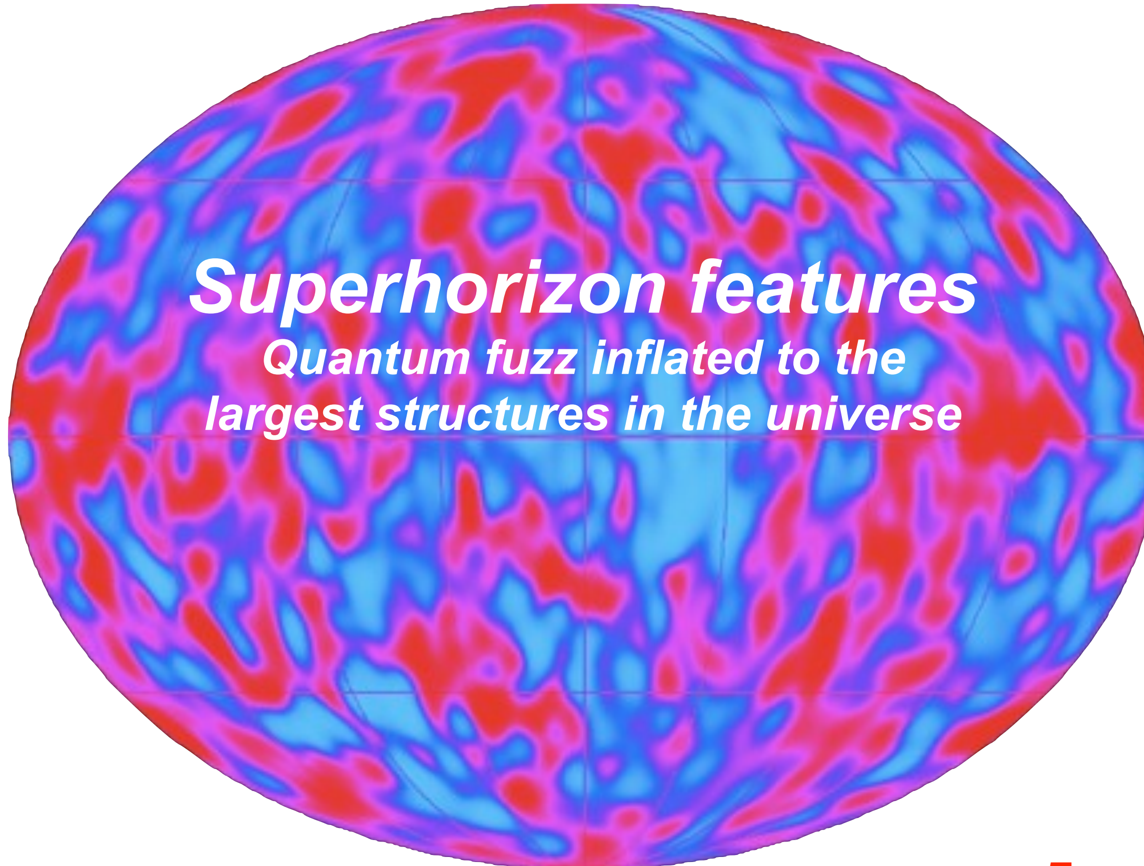


COBE Satellite

Smooth to a part in 10^5

the smoothness problem -
led to Inflation theory

Structure in background discovered in 1992



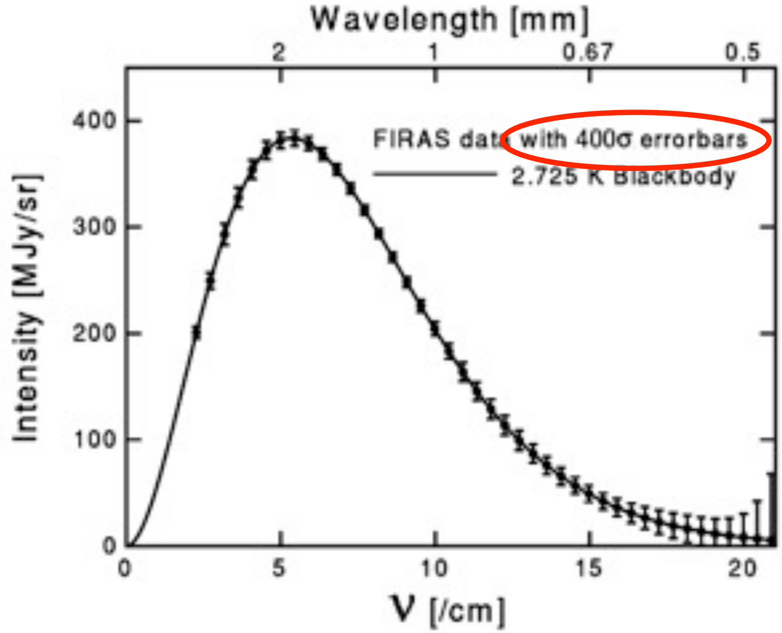
Superhorizon features

Quantum fuzz inflated to the largest structures in the universe

COBE Satellite

Smooth to a part in 10^5

the smoothness problem - led to Inflation theory



...und discovered in 1992

Superhorizon features

Quantum fuzz inflated to the largest structures in the universe

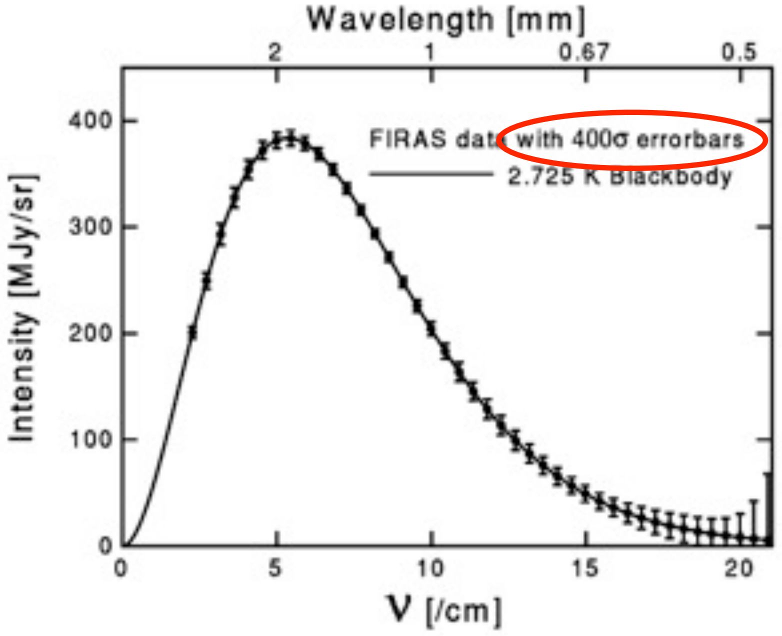
COBE Satellite

Smooth to a part in 10^5

the smoothness problem - led to Inflation theory

und di

COBE team leaders
John Mather & George Smoot*
received 2006 Nobel Prize



Superhorizon features

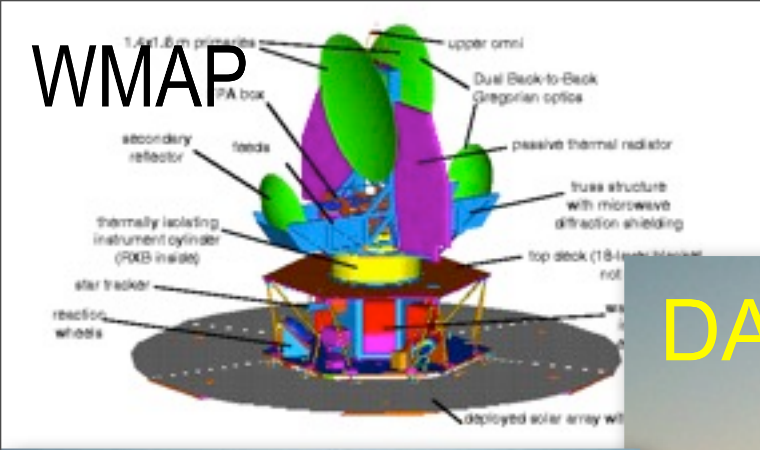
Quantum fuzz inflated to the largest structures in the universe

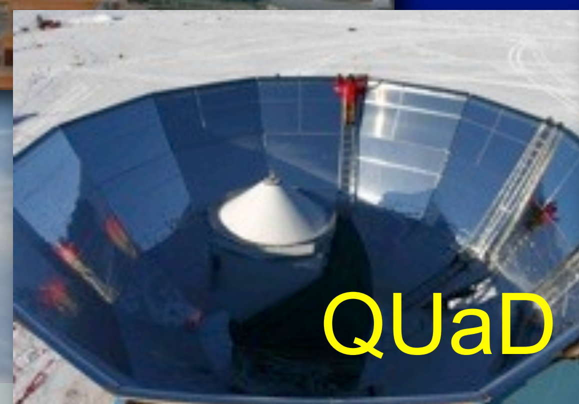
COBE Satellite

Smooth to a part in 10^5

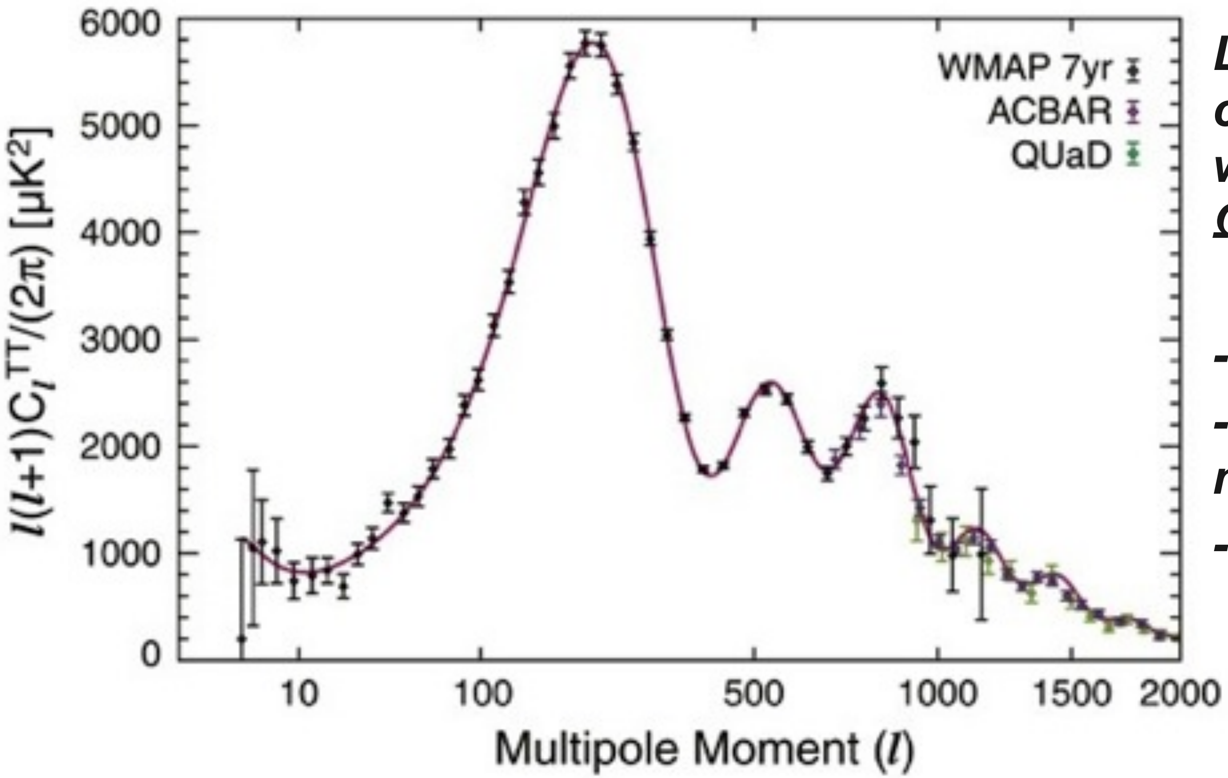
the smoothness problem - led to Inflation theory

push to finer angular scales...





Incredible progress



Line is fit to a flat ΛCDM cosmology model with just six parameters: $\Omega_b h^2$, $\Omega_m h^2$, A_s, τ, n_s, Ω_Λ

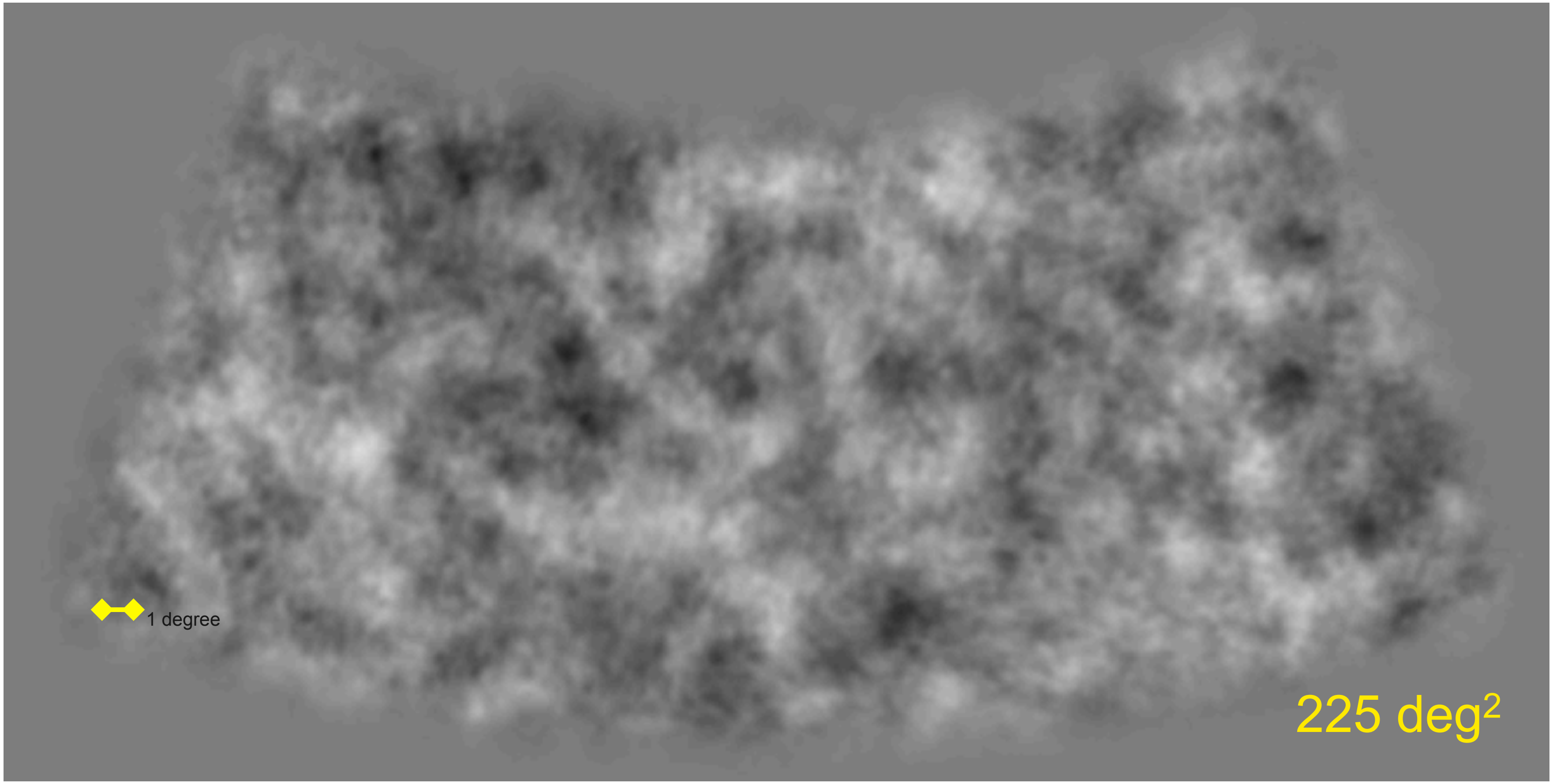
- ***Inflation (flat, n_s)***
- ***Non-baryonic dark matter (3rd peak)***
- ***Dark Energy***

What's next? "B-mode" CMB polarization to probe Inflation.

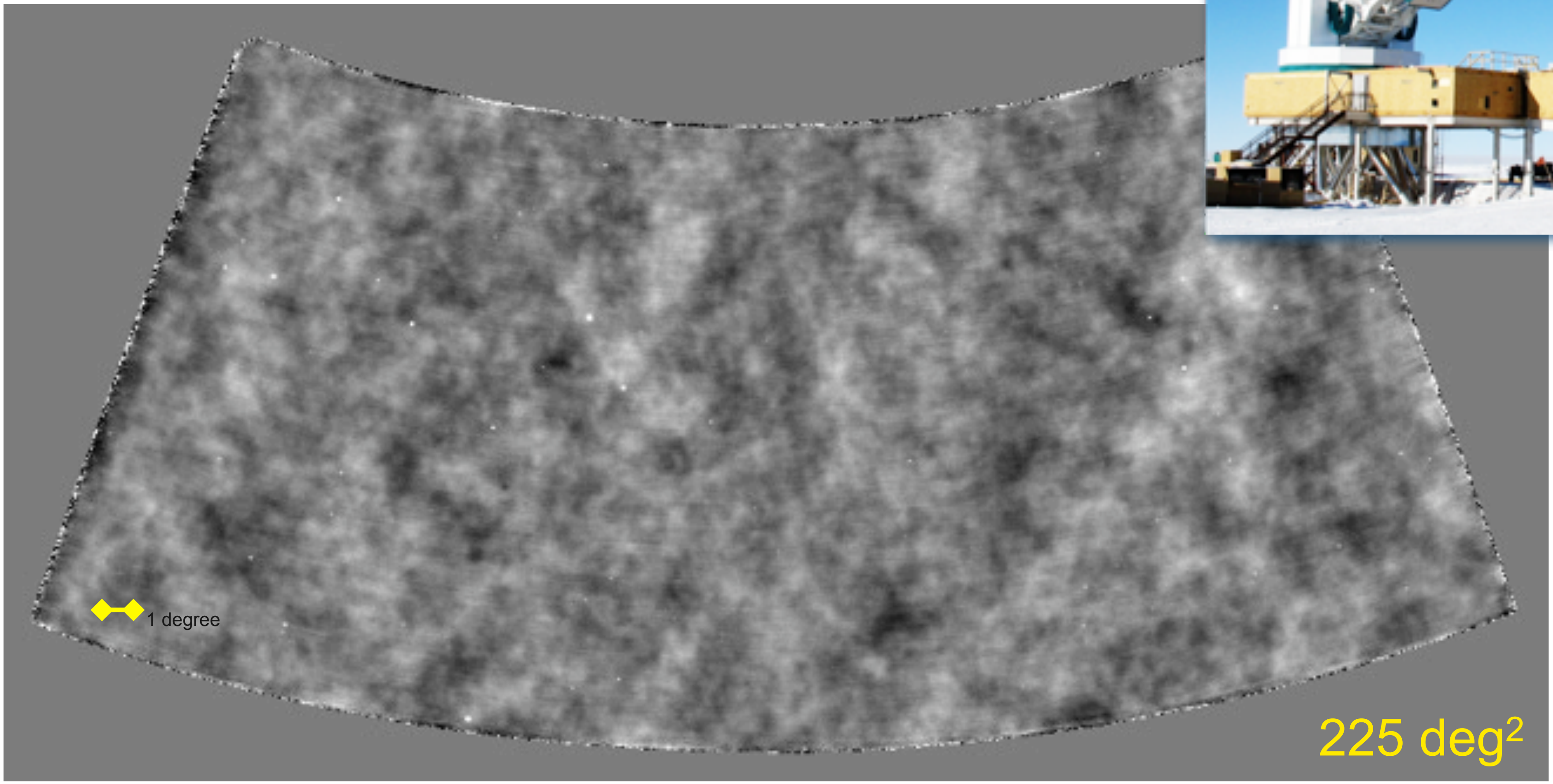
The data from SPTpol will constrain the masses of the neutrinos and set (or limit) the energy scale of Inflation.

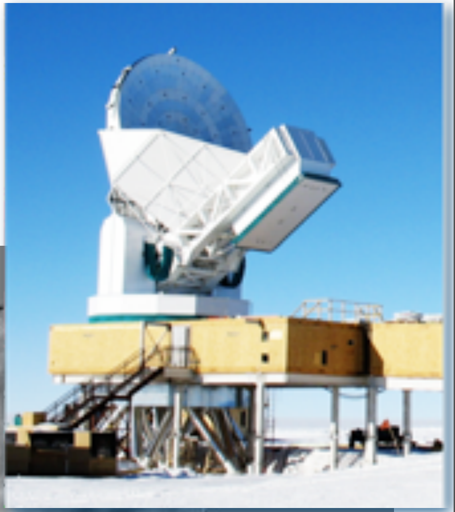
Komatsu et al., arXiv:1001:4538; Larson et al., arXiv:1001.4635

WMAP CMB map covering one of the SPT fields



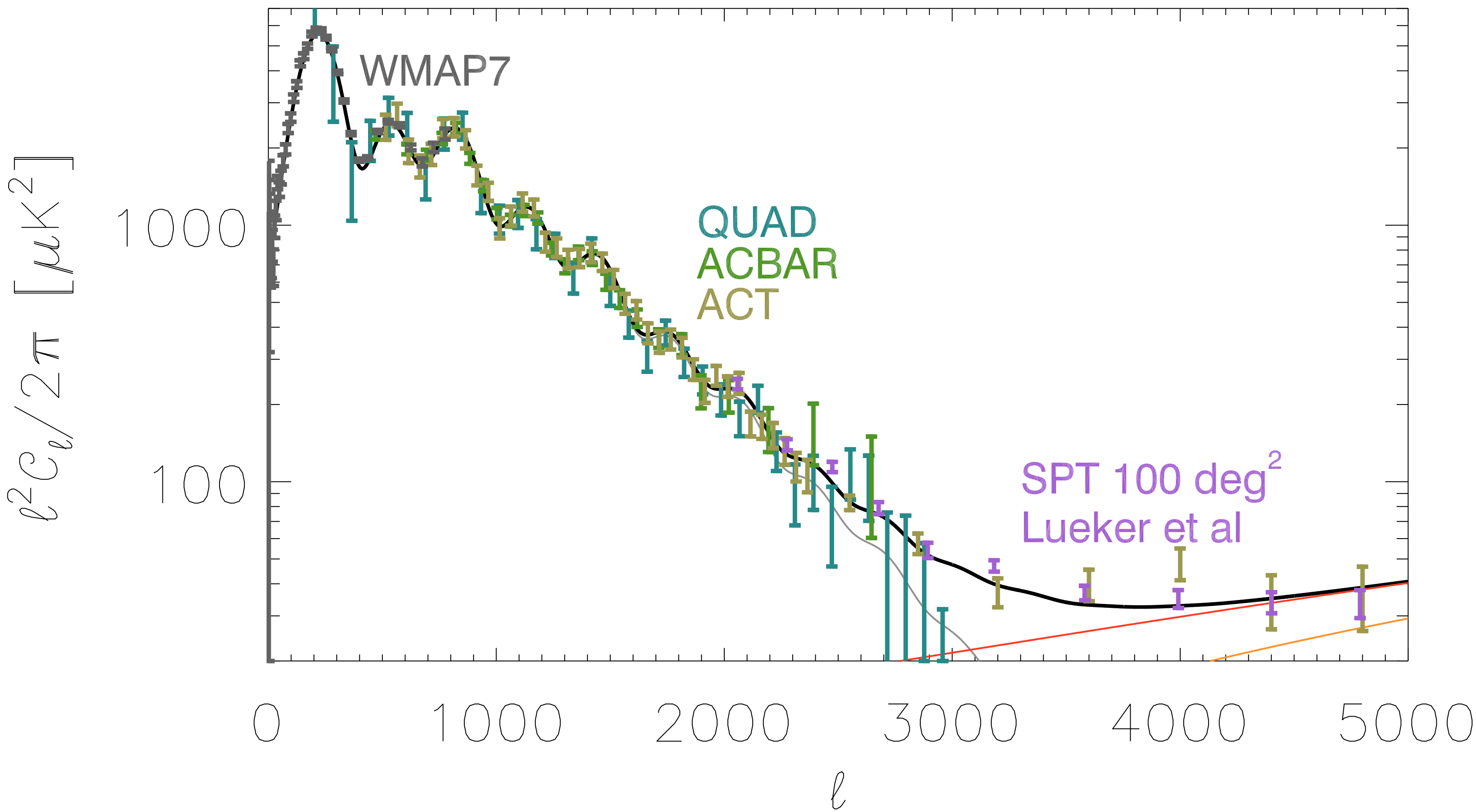
Lightly filtered SPT map at 90 GHz





Shows structure from degrees to arc minutes:
from large-scale CMB to SZ & unresolved sources.

To finer angular scale anisotropy: SPT 1st detection of secondary CMB anisotropy

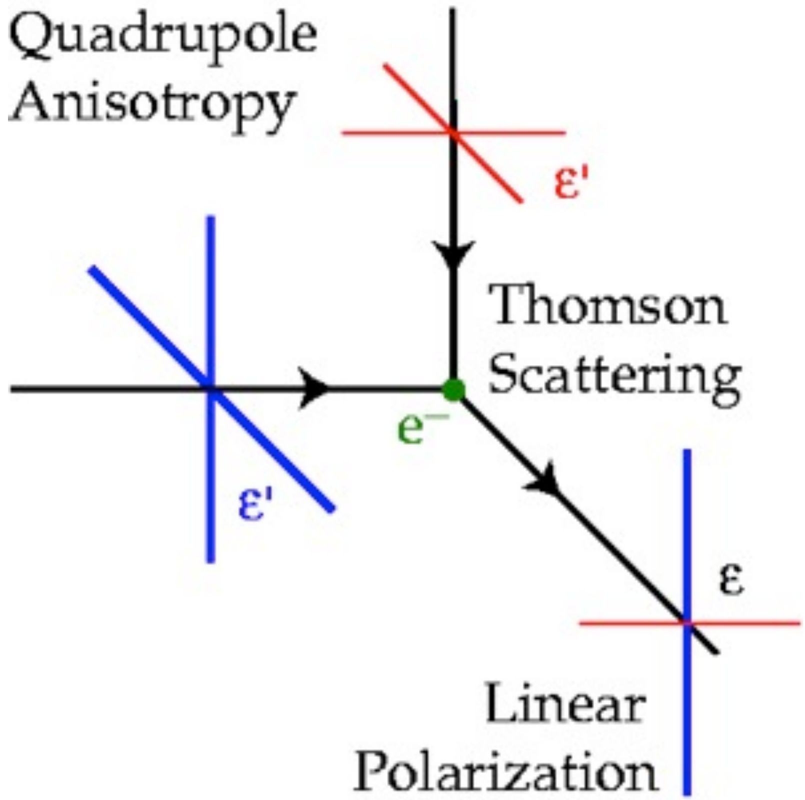


Newest SPT results:

NOT FOR DISTRIBUTION

Polarization of the CMB

Due to Thomson scattering –
CMB must be polarized



from W. Hu's web page

Polarization of the CMB

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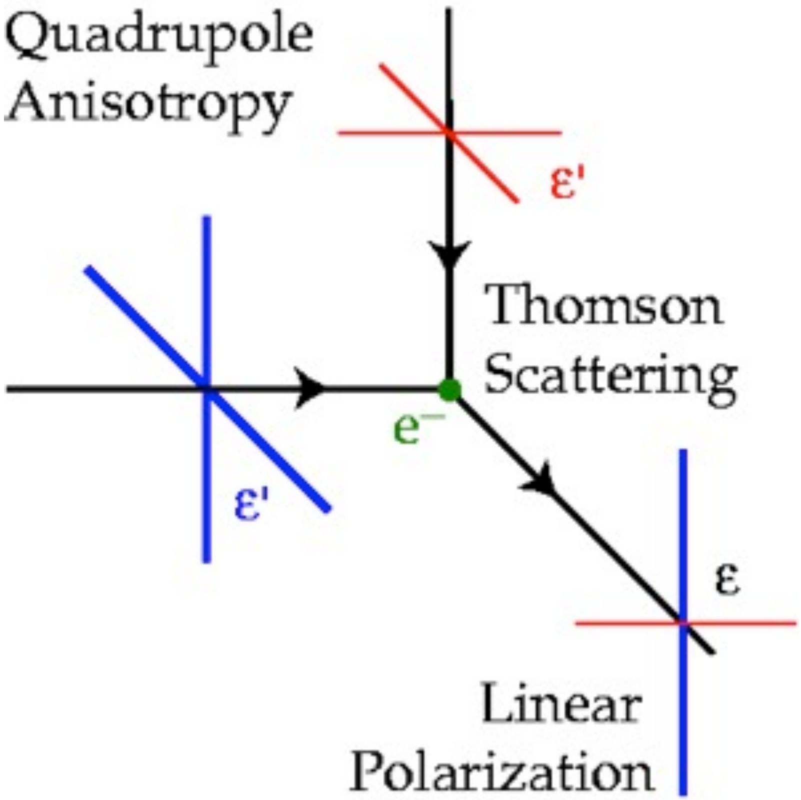
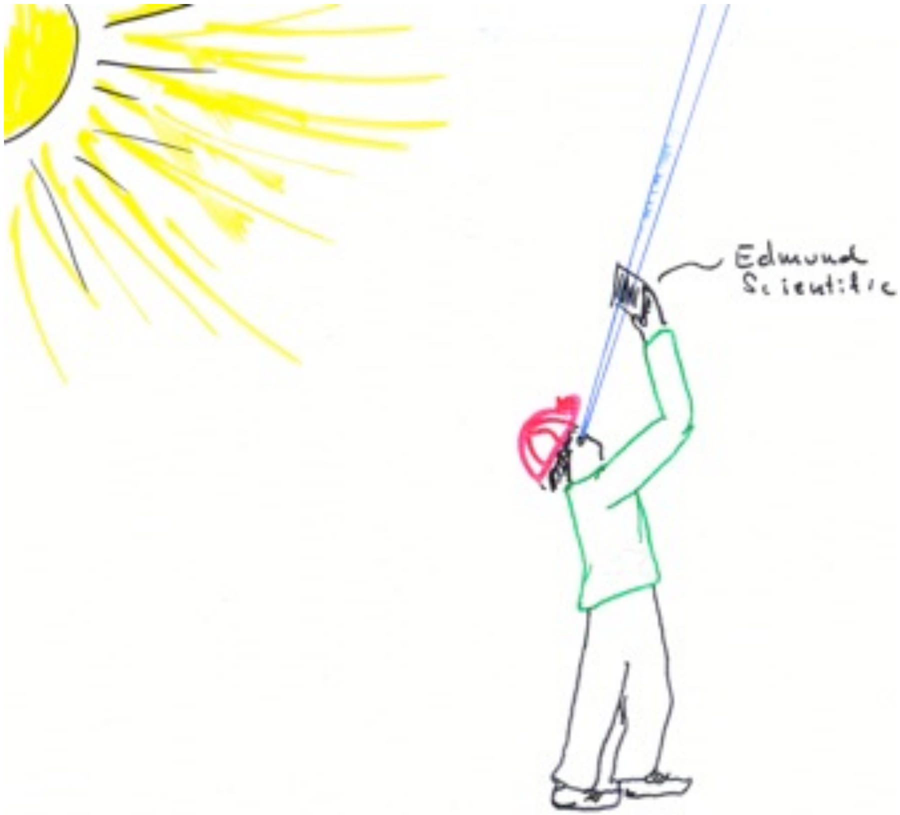
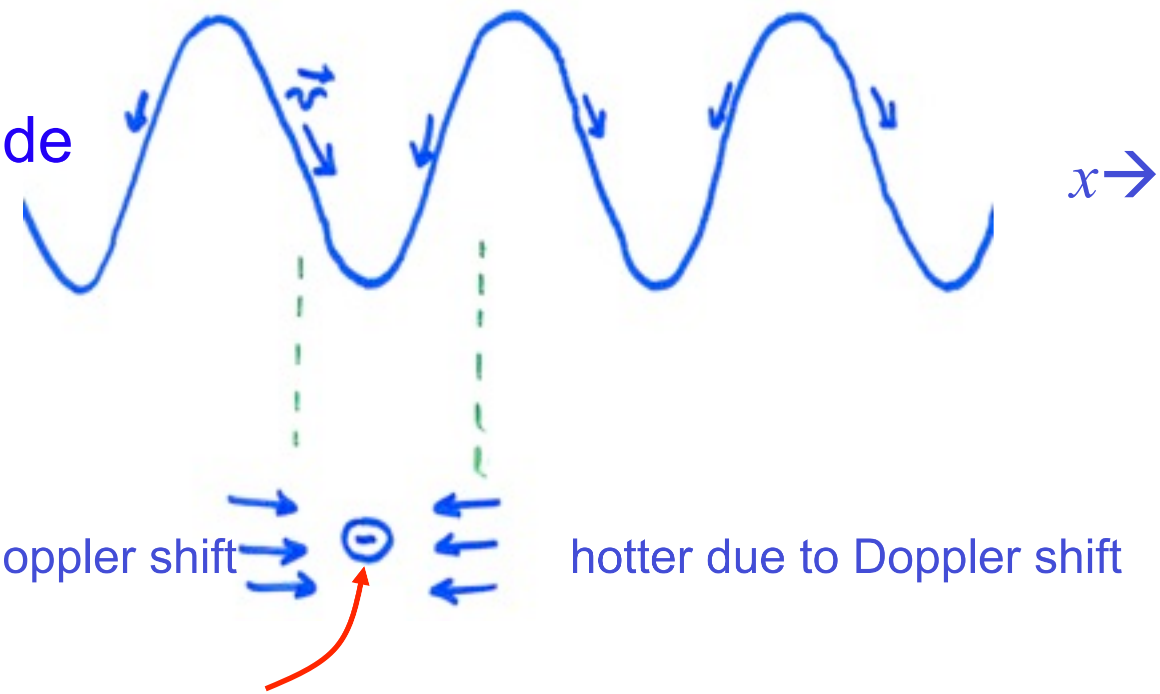




from W. Hu's web page

Generating CMB polarization

Density mode



Before decoupling:

- electron ‘sees’ only a local monopole

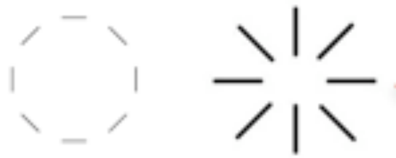
During decoupling:

- mean free path increases and electron ‘sees’ quadrupole
- scattered light is polarized

E-mode from density modes (scalar fluctuations)

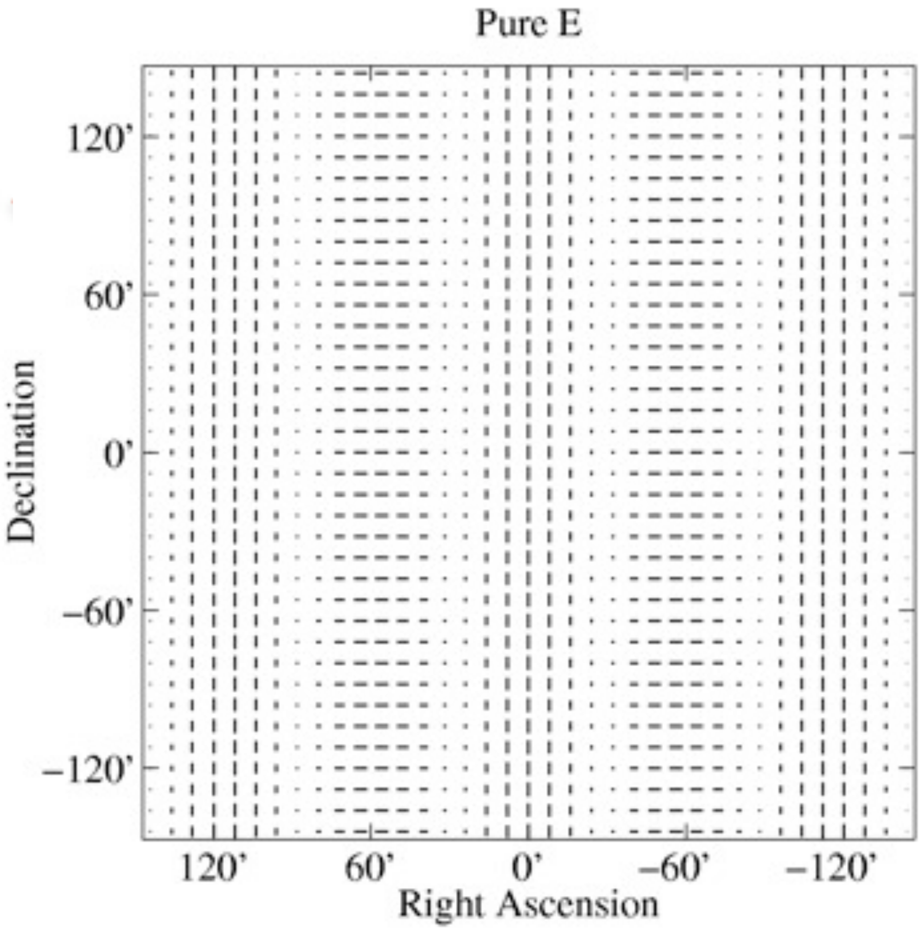
E-mode Polarization (Curl free)

Polarization parallel & perpendicular to wave vector



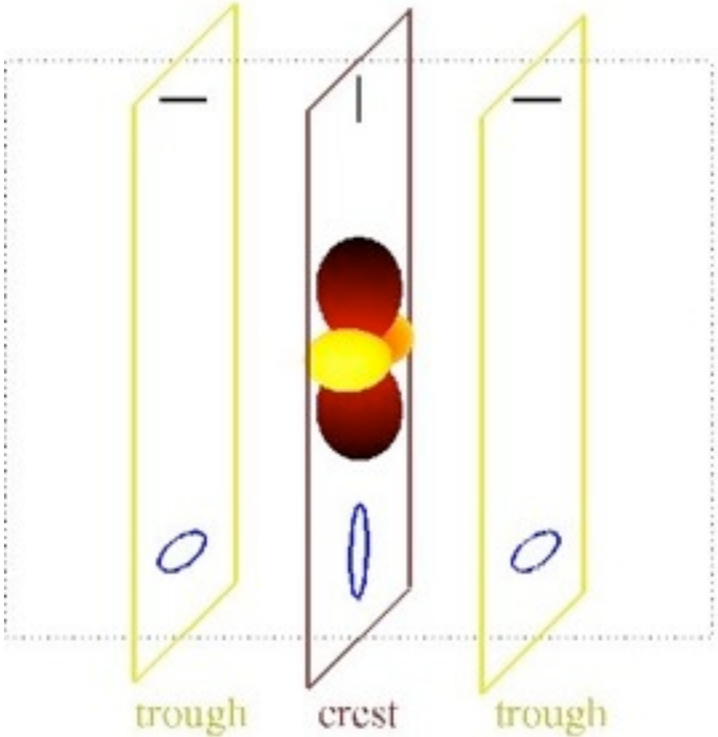
Even parity, curl-free

Density (scalar) fluctuations generate only E-Polarization



Gravitational wave induced CMB polarization

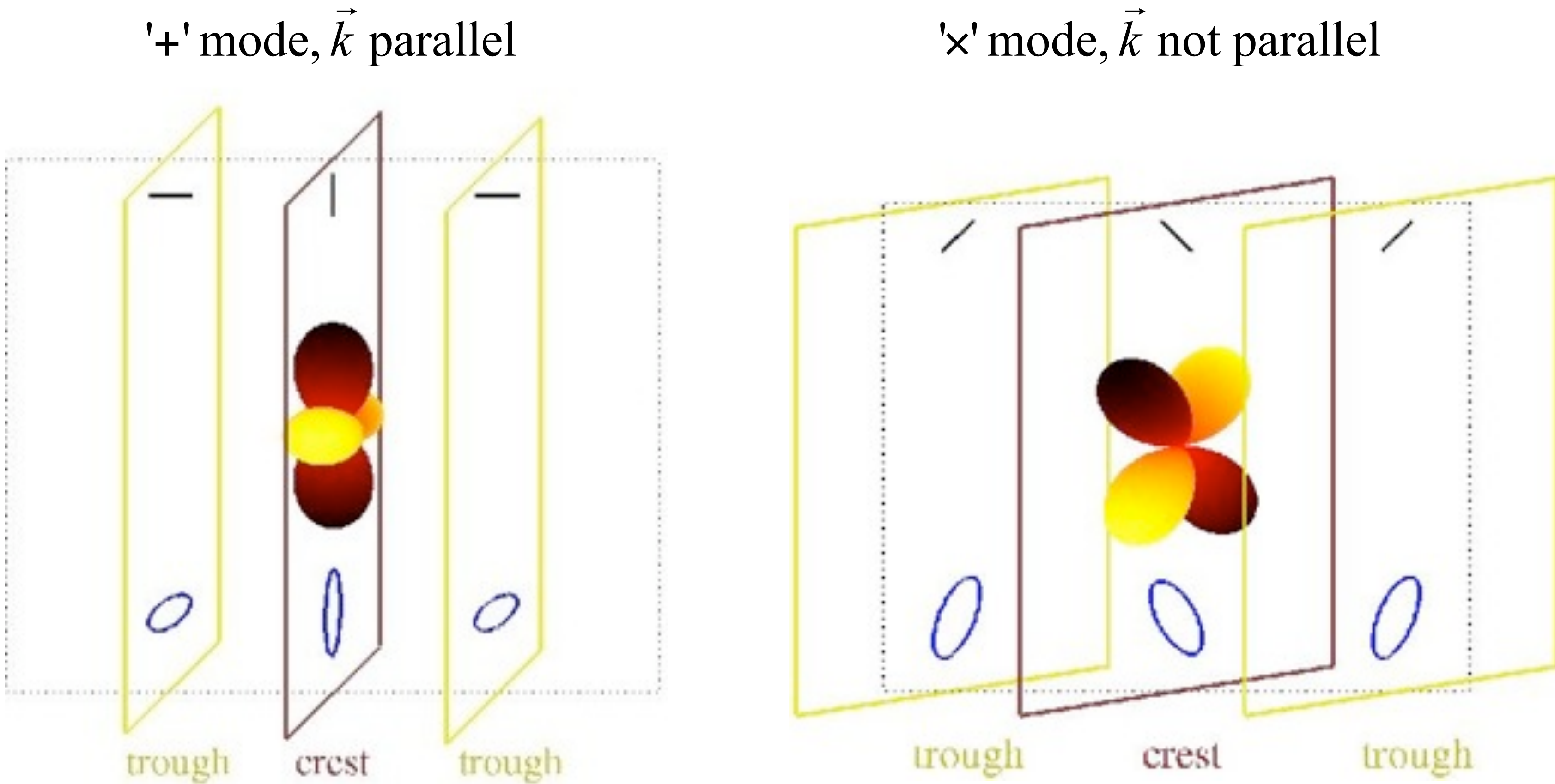
$'+'$ mode, $\vec{k}$ parallel



E-mode

Figure from John Kovac's thesis

Gravitational wave induced CMB polarization



E-mode

B-mode
(Inflationary GW B-modes)

Figure from John Kovac's thesis

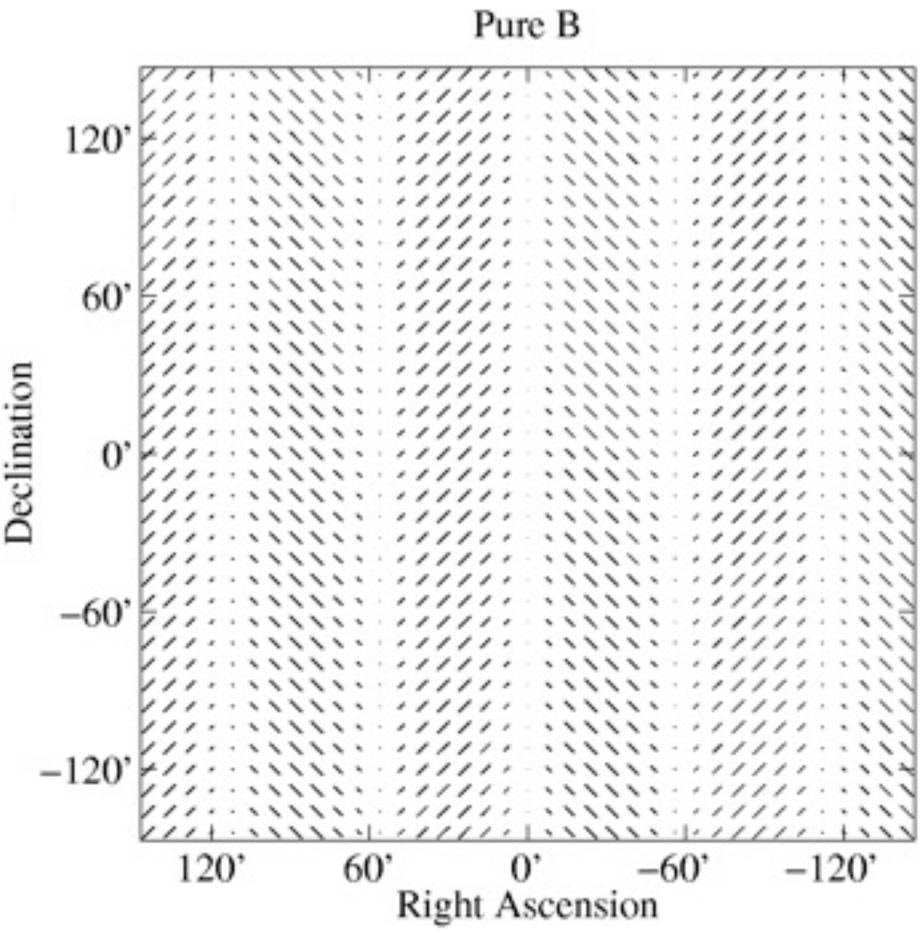
B-mode Polarization (div free)

Polarization oriented ±45 degrees
to wave vector

Odd parity, div free

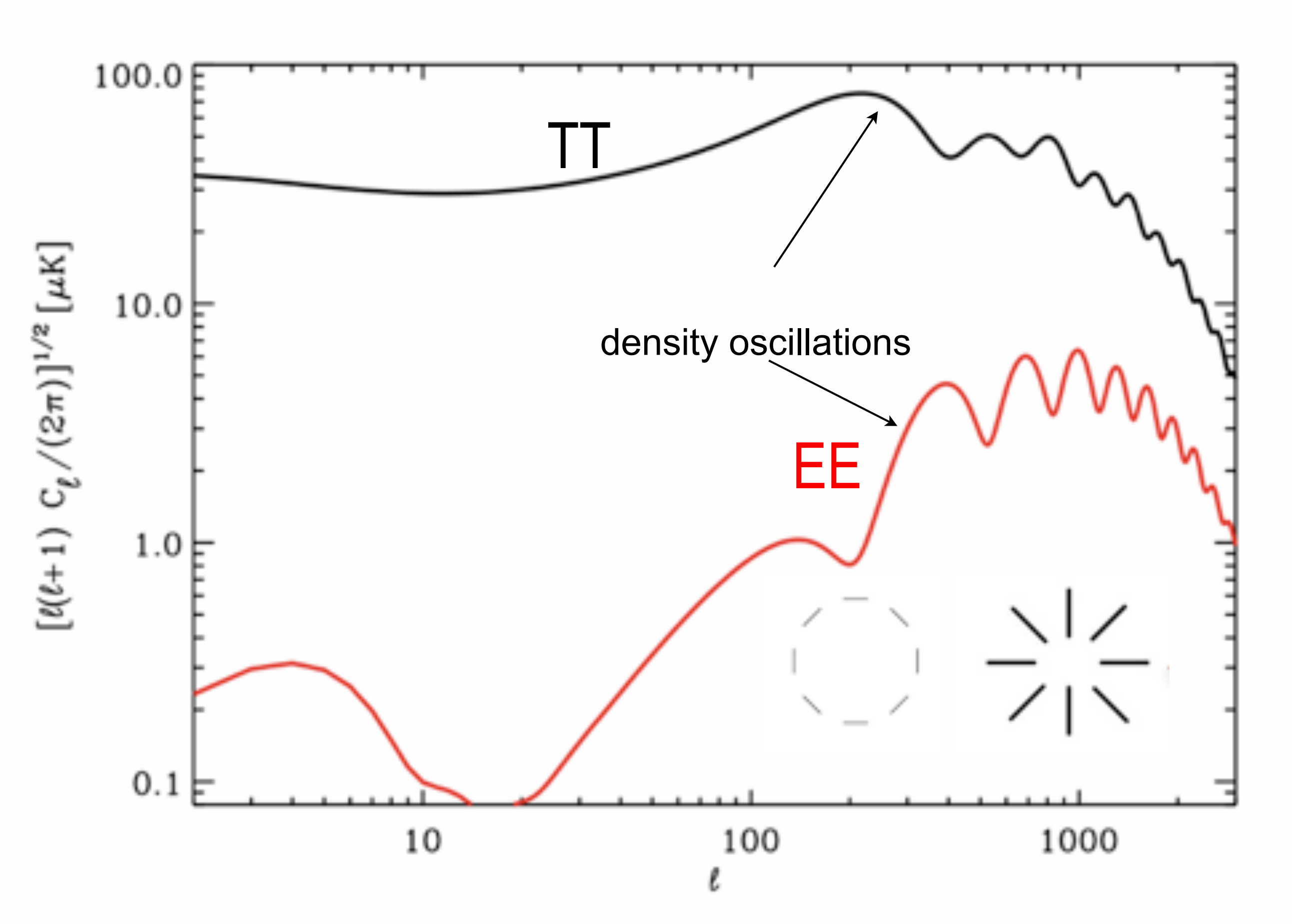
Can NOT be generated by the density fluctuations, but can be generated by gravitational waves sourced by Inflation in the first instants of the universe, 10^{-35} seconds, at GUT energies.

"Smoking gun" test of Inflation and direct measure of its energy scale



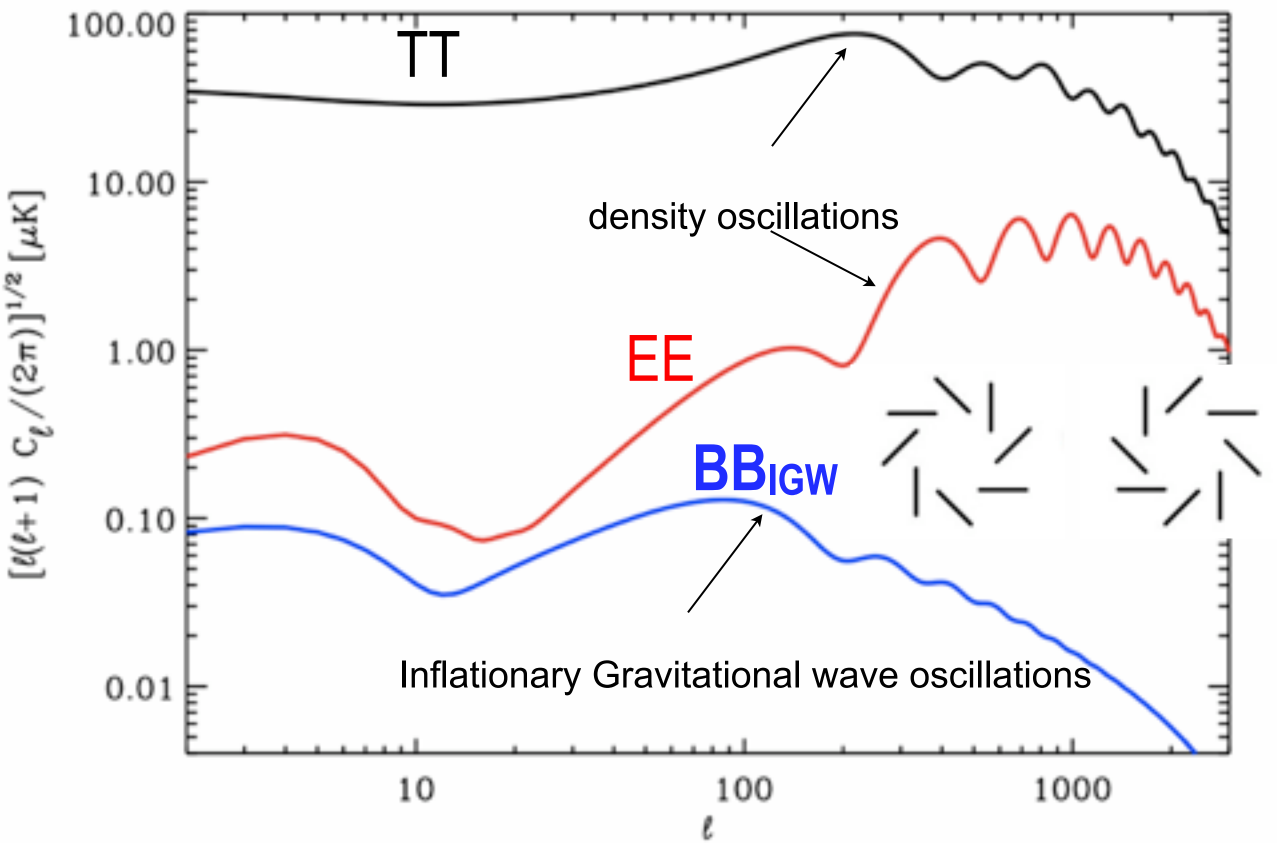
Argonne NATIONAL LABORATORY

CMB polarization

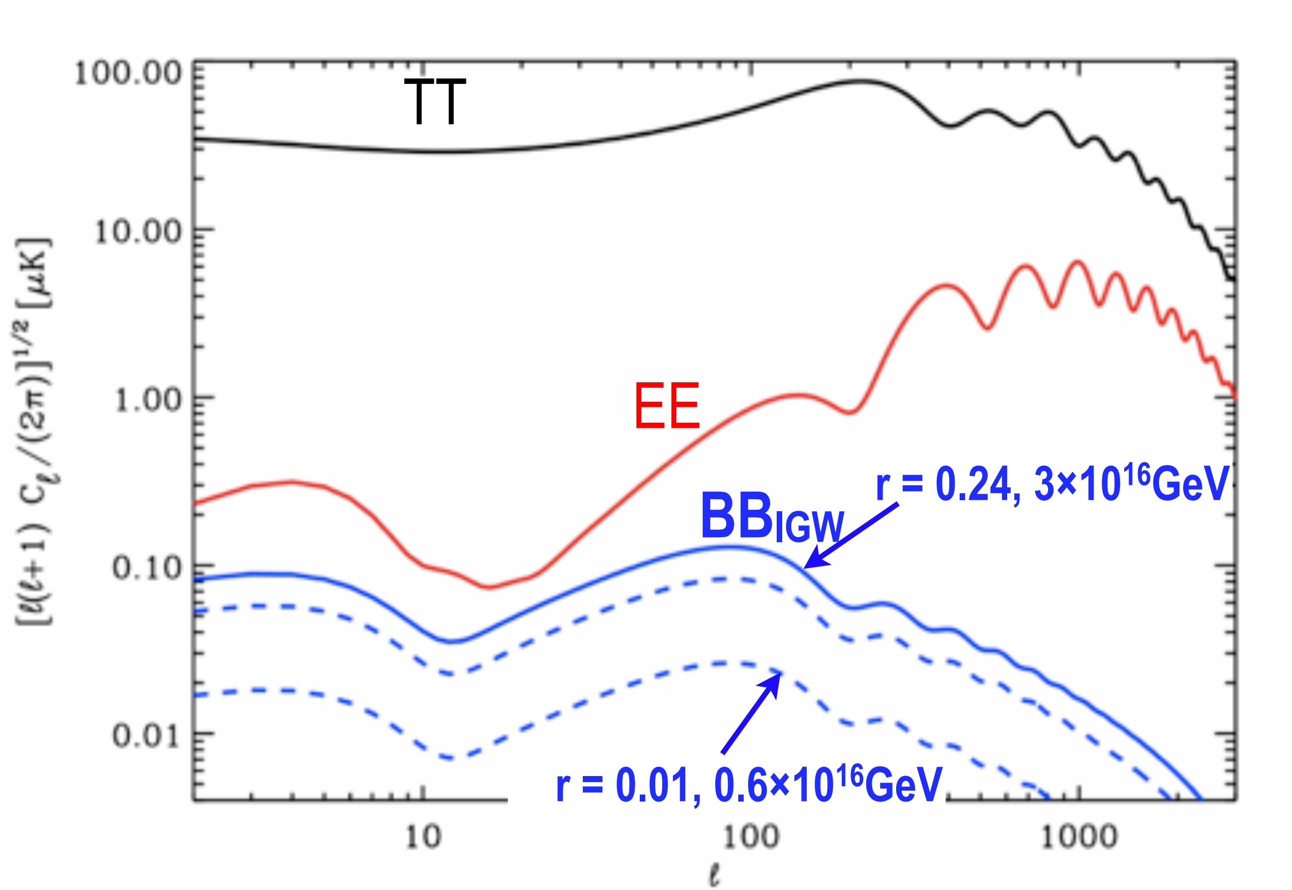


Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

CMB polarization

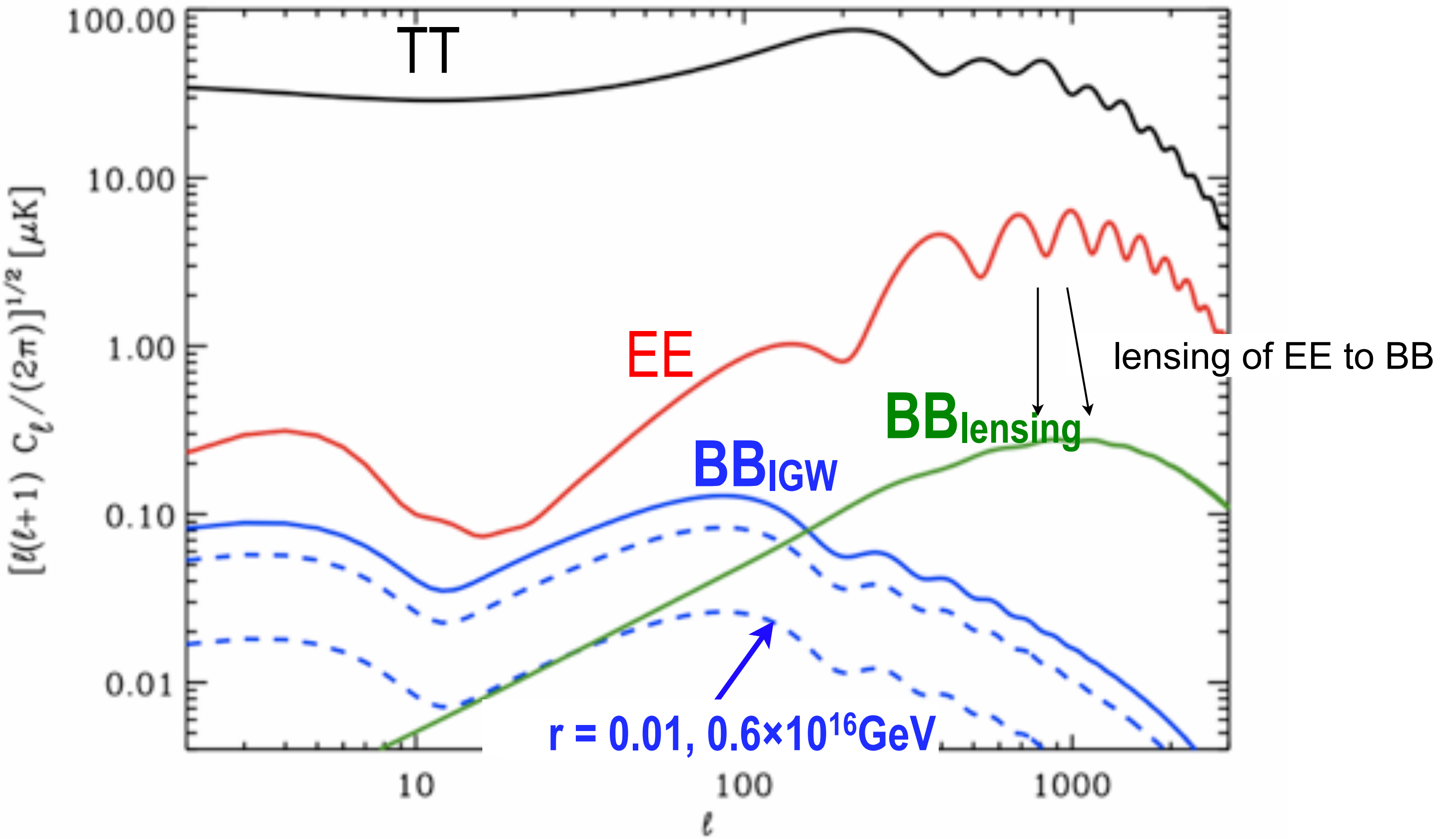


CMB polarization

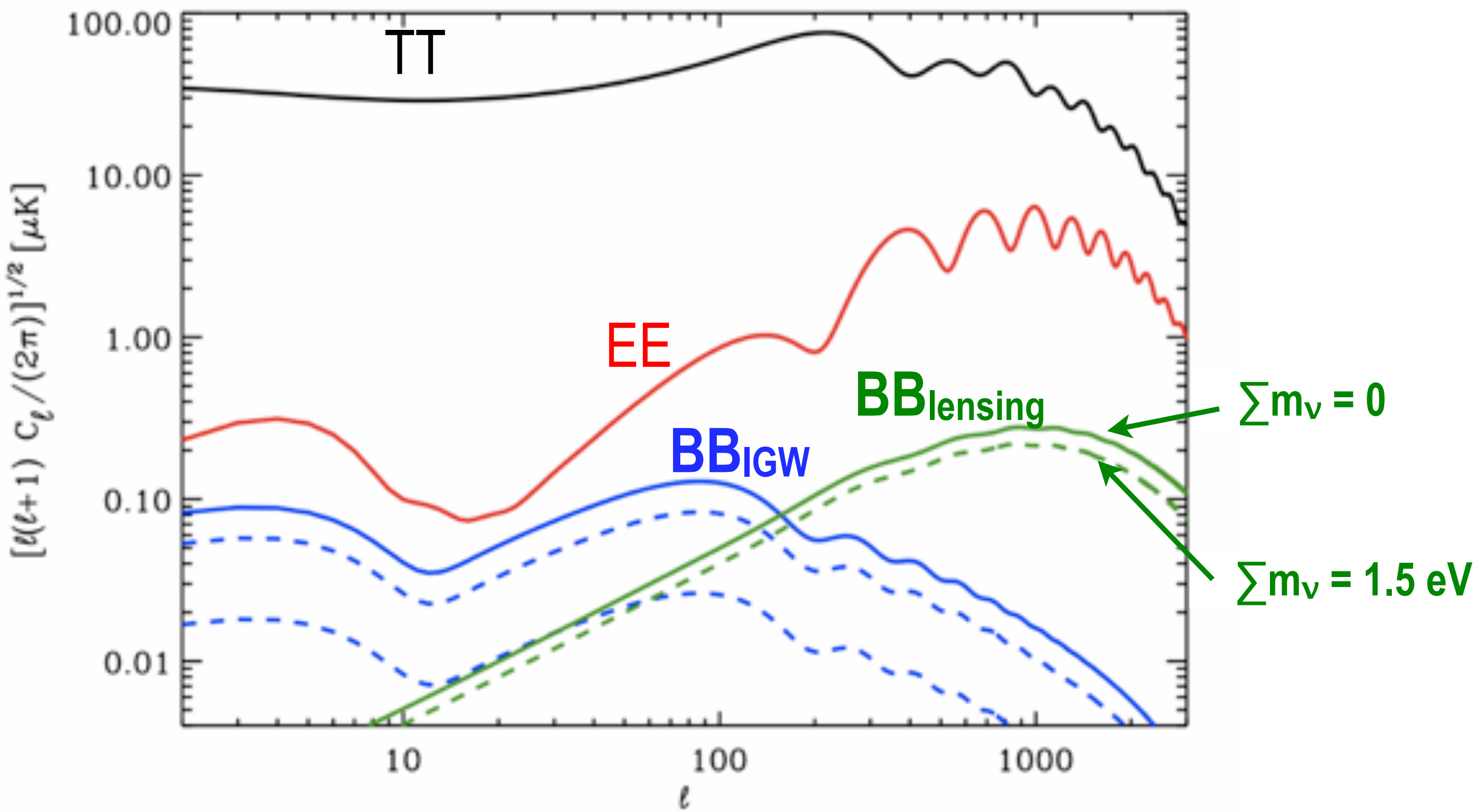


r is the tensor to scalar ratio of the primordial fluctuations

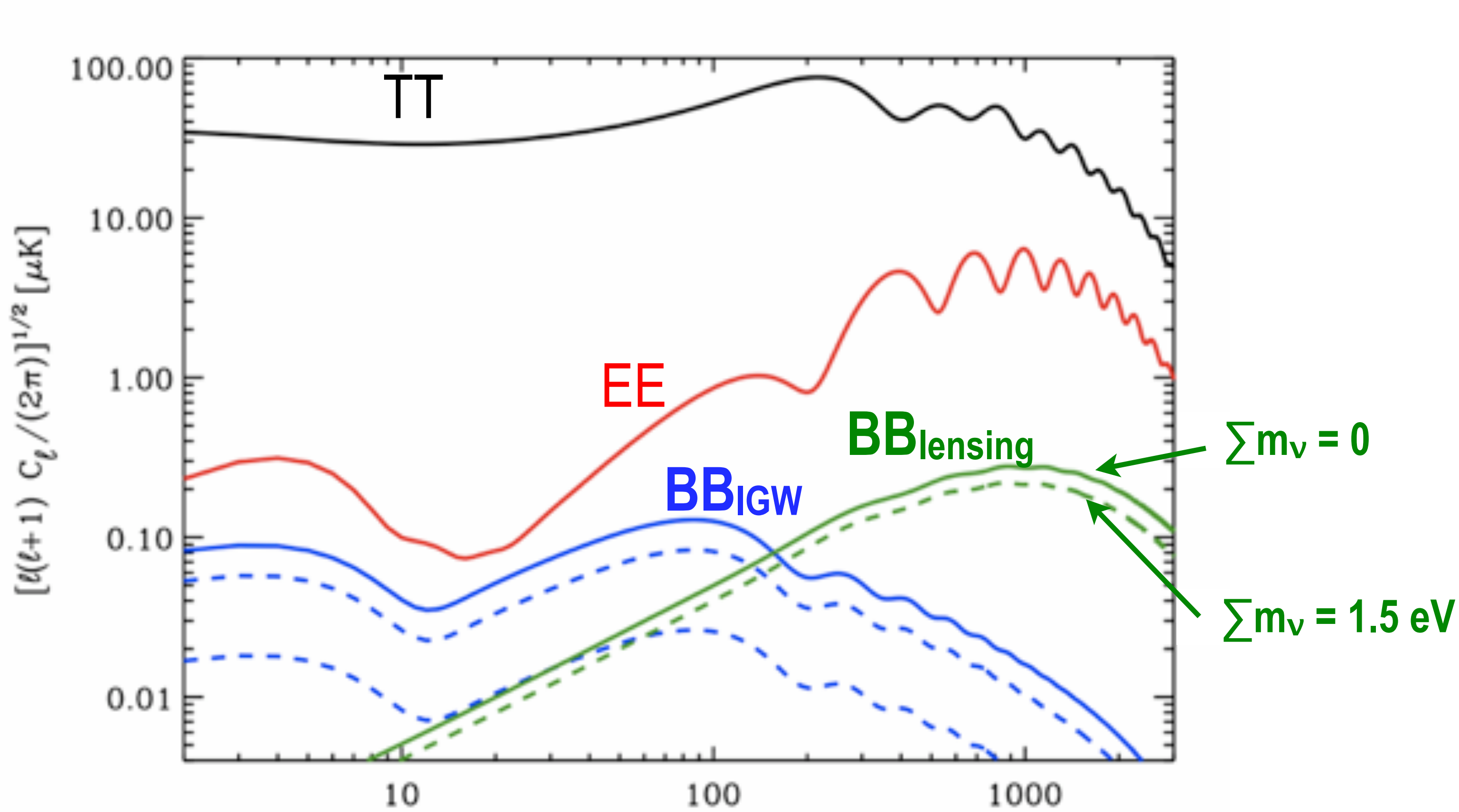
CMB polarization



CMB polarization

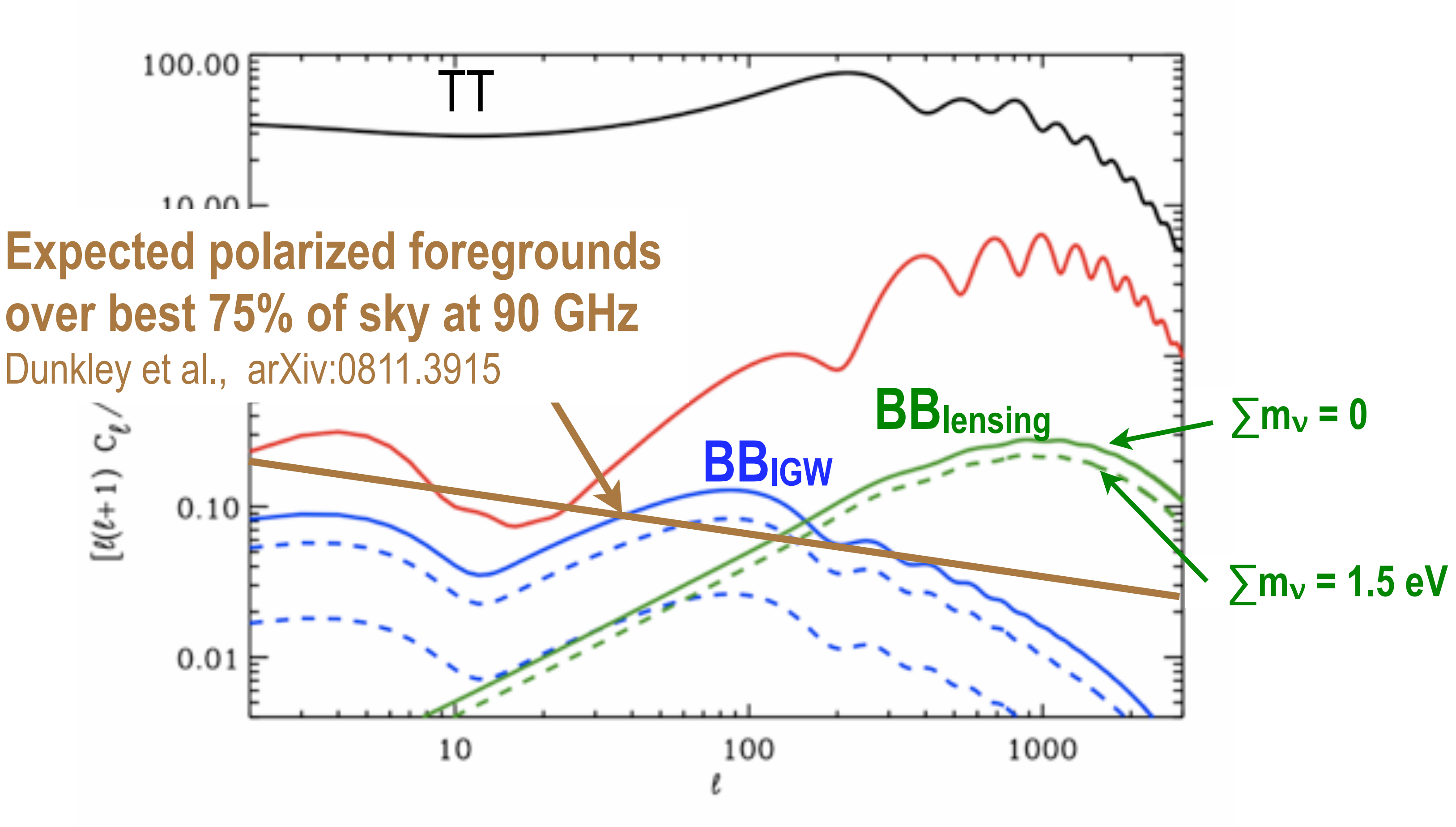


CMB polarization



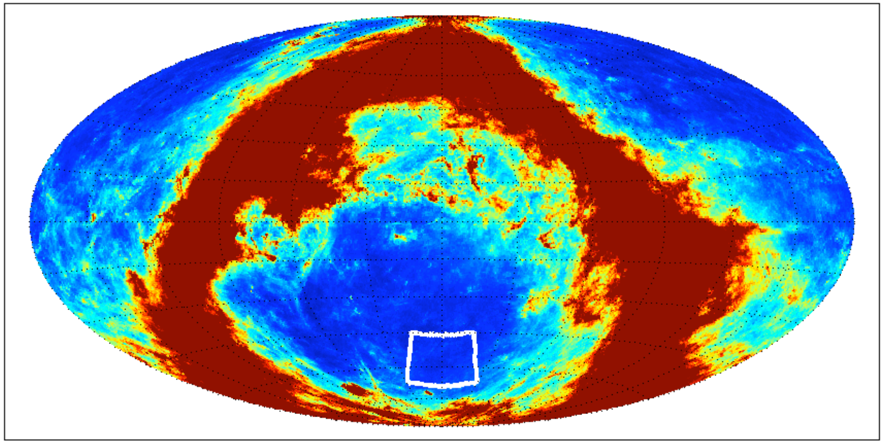
CMB measurements should be able to achieve $\sigma(\sum m_\nu) = 0.05$eV, comparable to Δm measured by neutrino oscillations.

CMB polarization

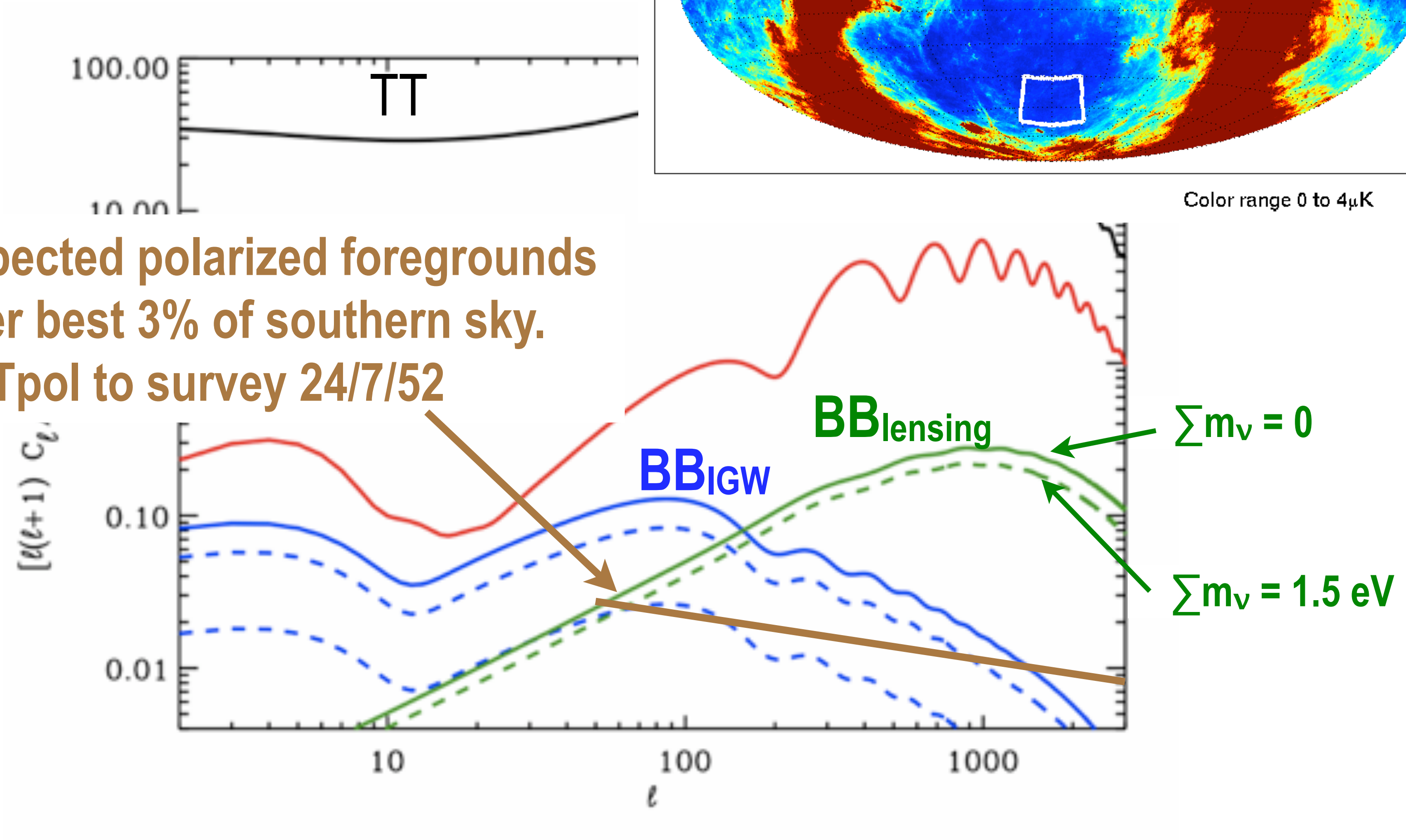


CMB polarization

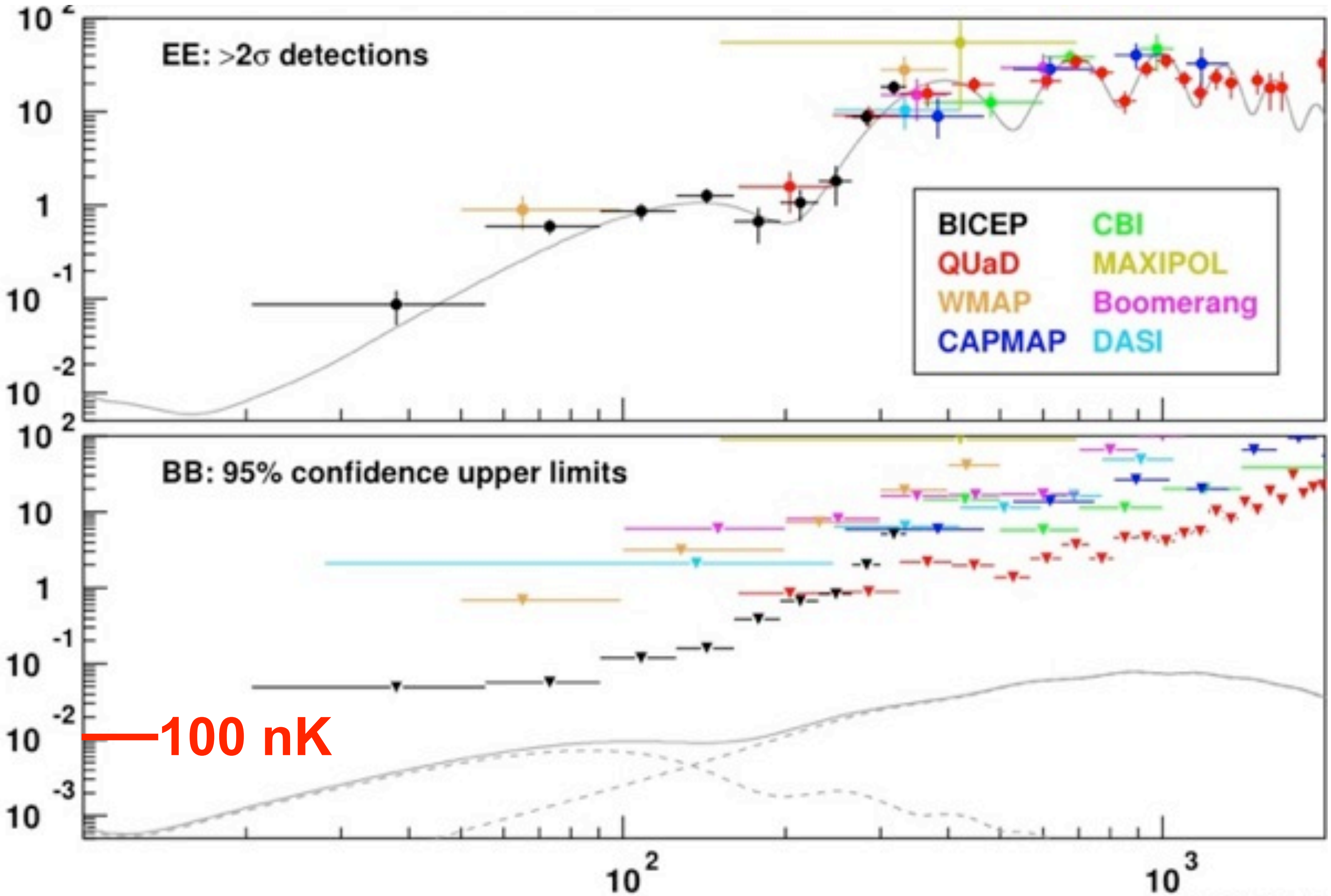
Predicted foreground polarization at 150GHz



Color range 0 to 4μK



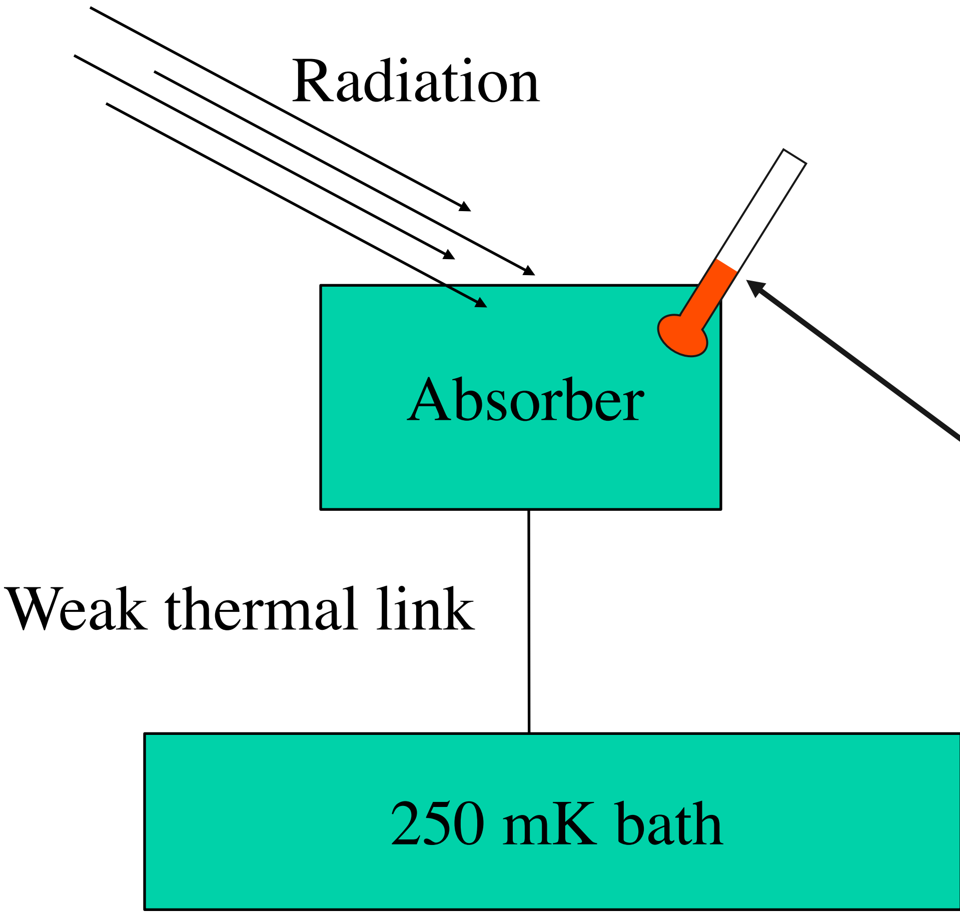
Closing in on inflation

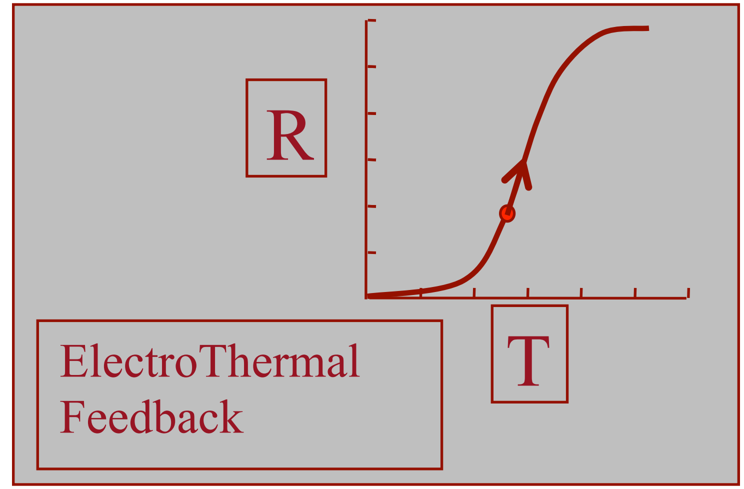


see Brown et al., arXiv:0906.1003 & Chiang et al., arXiv:0906.1181

Need more sensitivity! Need scalable, background limited, detectors.

Bolometry: A Broadly Applicable, Ultra-Sensitive Thermal Detection



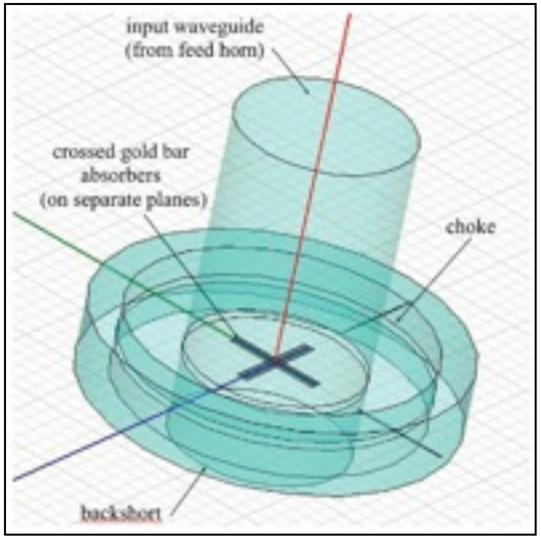


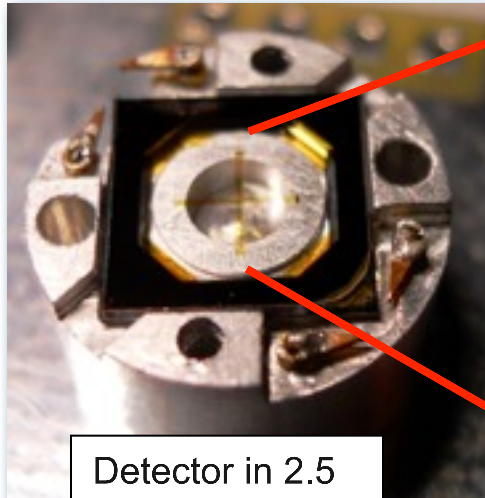
Thermometer: Voltage biased transition edge sensor (TES).

Measure incident power (pW) by change in bias current using SQUIDS.

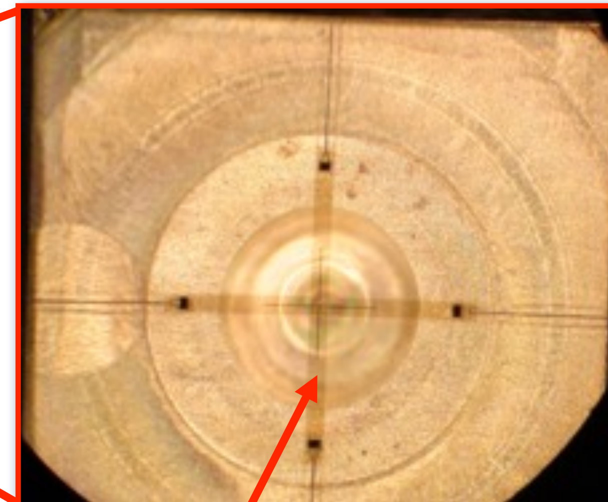
Apparent simplicity is deceptive!

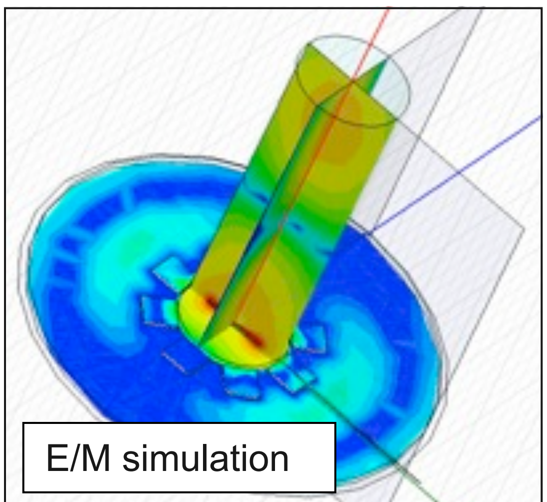
LDRD developed Argonne SPTpol TES Detector



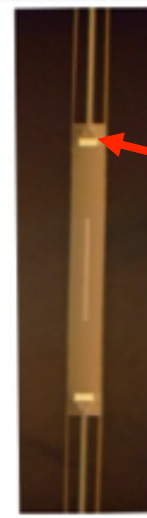


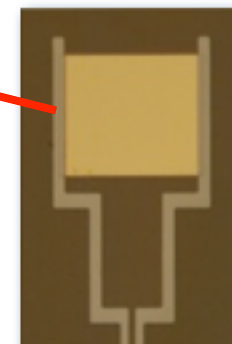
Detector in 2.5 mm waveguide mount





E/M simulation





Mo/Au proximity effect 500mK T_C bilayer TES

Challenges met

- high optical coupling
- excellent polarization isolation
- background limited sensitivity
- optimized operational bandwidth and electrical properties for multiplexing
- detailed RF simulations
- materials characterization
- thermal modeling
- high throughput production
- achieve high uniformity of properties

"Optical Properties of Argonne/KICP TES Bolometers for CMB Polarimetry." AIP volume 1185, pages 203-206, 2009. doi: 10.1063/1.3292315.

"TES Development for a Frequency Selective Bolometer Camera." IEEE Transactions on Applied Superconductivity, 19:548-552, June 2009. doi: 10.1109/TASC.2009.2017954.

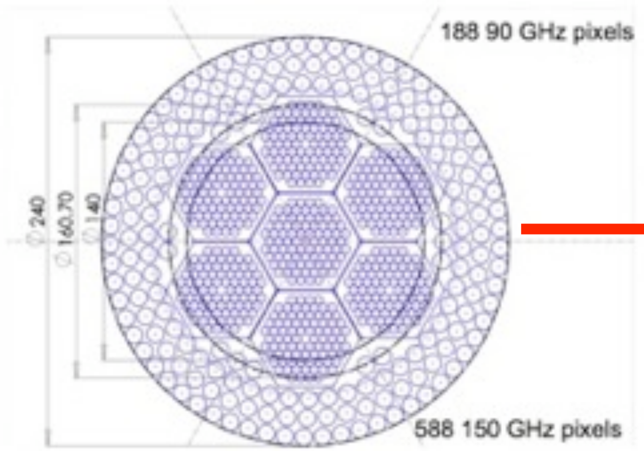
"Optical design of Argonne/KICP Detectors for CMB Polarization." AIP,volume 1185, pages 487-489,2009b. doi: 10.1063/1.3292384.

"Design and Fabrication of Argonne/KICP Detectors for CMB Polarization." AIP, volume 1185, pages 359-362,2009. doi: 10.1063/1.3292352.

"Low temperature Thermal Transport in Partially Perforated Silicon Nitride Membranes." Applied Physics Letters, 94(18):183504,May 2009a. arXiv:0906.2956.

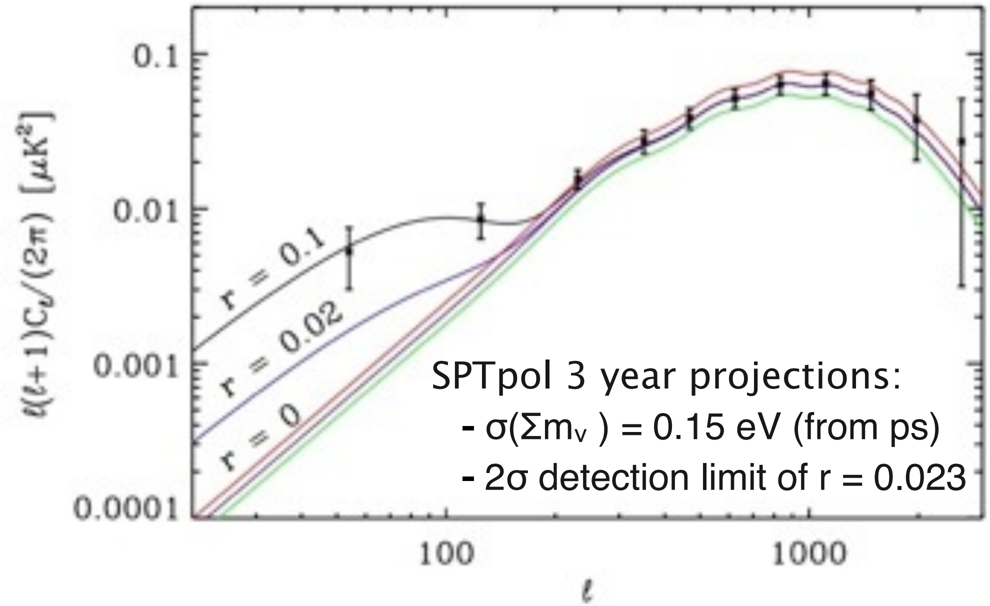
"Control of Membrane Thermal Transport Supporting Superconducting Detector Development." IEEE Transactions on Applied Superconductivity, 19:489-492, June 2009b. doi: 10.1109/TASC.2009.2019564.

FY11-13 Plan for CMB Thrust:



A) Deploy SPTpol (11/2011)

ANL providing 90 GHz channel and participating in SPTpol & ongoing dark energy data analysis.



FY11-13 Plan for CMB Thrust:

B) Expand Argonne bolometer technology for future CMB experiments

Targeting additional 10-100x increase in sensitivity
- *monolithic array fabrication*
- *superconducting microstrip coupling*
- *multi-chroic detectors (many passbands on a single pixel)*

Increased sensitivity requires expanded readout capacity
- *further develop current multiplexing readout technology*
- *integrate new microwave readout techniques*

Upgrade SPTpol in 2014

Provide detectors for next generation CMB missions, e.g., Polar

Synergy with lab-wide detector developments, e.g., led to $5M DOE Early Career Award to A. Micelli for spin-off R&D for Advance Photon Source (APS) detectors.

FY11-13 Plan for CMB Thrust:

People:

Current Argonne personnel:

Staff Scientist: C. Chang (0.5 FTE HEP & 0.5 UChicago)
J. Carlstrom (joint UChicago)
V. Novosad (ANL/MSD)

Postdocs: A. Datesman & G. Wang (2.0 FTE LDRD)

Fabrication engineer: V. Yefremenko (1.0 FTE LDRD)

Technician: J. Pearson (MSD)

FY11-FY13 HEP request:

Staff Scientist: 1.5 FTE

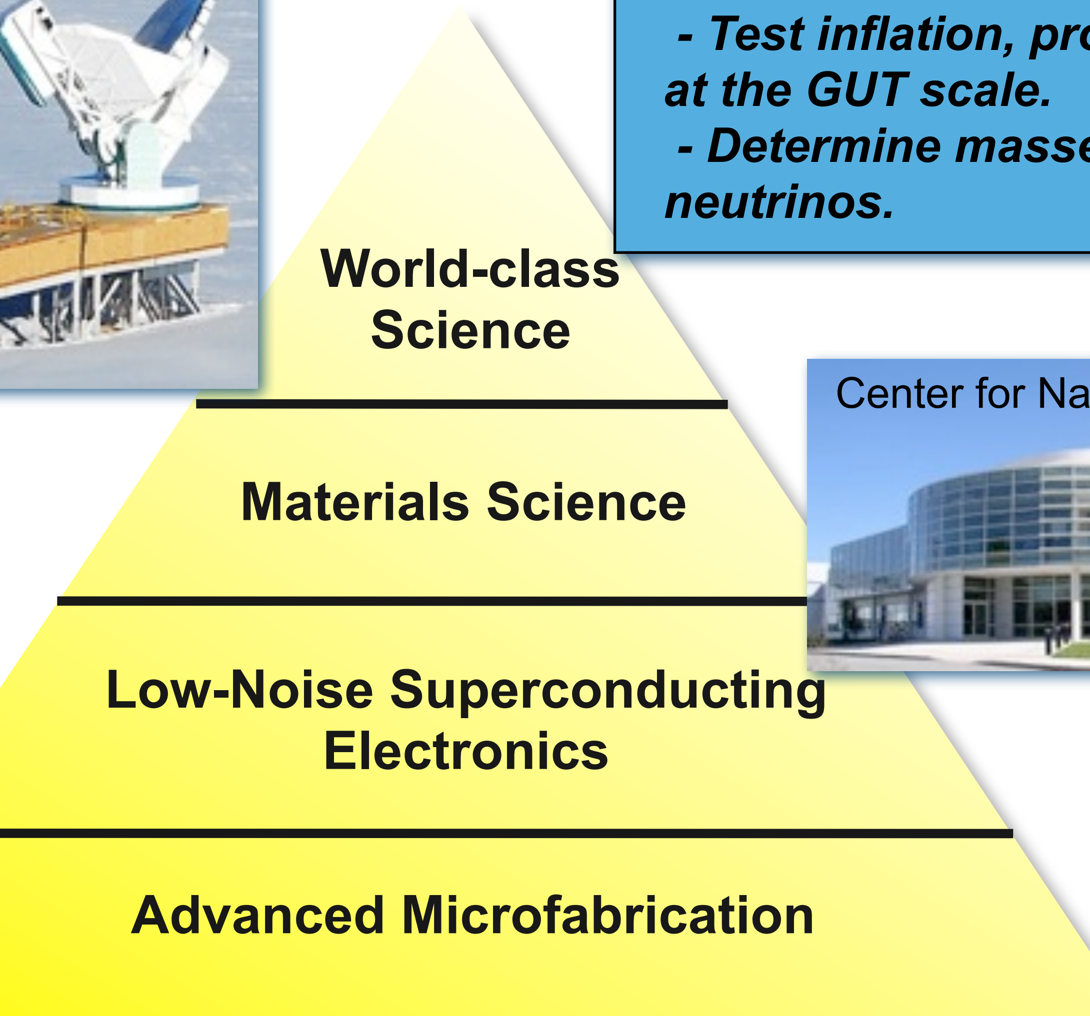
Postdocs: 2.0 FTE

Fabrication engineer: 1.0 FTE

We're ready to go

The South Pole Telescope

Cosmic Frontier of DOE/HEP:
- Test inflation, probe physics at the GUT scale.
- Determine masses of the neutrinos.



Center for Nanoscale Materials

Back up slides

Argonne Strategic Investment into CMB science

LDRD Seeded

- Successful development of bolometers for CMB pol
- Spin-off efforts in x-ray detectors

ANL HEP Commitment

- Joint appointments w/ KICP at U. Chicago
- Synergy with local cosmology efforts at FNAL and KICP

Dedicated MSD resources

- Unique microfabrication & materials expertise
- Provided exclusive deposition system
- Access to CNM

Scientific Opportunity

- Exploring new Inflation parameter space
- Synergy with DE science (DES + SPT)

CMB polarization experiments (http://cmbpol.uchicago.edu/)

Table 1: Future Suborbital CMB Polarization Experiments.

	Technology	FWHM (arcmin)	Frequency (GHz)	Detector Pairs	Modulator
US-led balloon-borne:					
EBEX (Oxley et al., 2004)	TES	8	150/250/410	398/199/141	HWP
Spider (Montroy et al., 2006)	TES	60/40/30	96/145/225	288/512/512	HWP/Scan
PIPER I	TES	21/15	200/270	2560/2560	VPM
PIPER II	TES	14	350/600	2560/2560	VPM
US-led ground-based:					
ABS(Staggs et al., 2008)	TES	30	150	200	HWP
ACTpol(Fowler et al., 2007)	TES	2.2/1.4/1.1	90/145/217	$\sim$ 1000	Scan
BICEP 2(Nguyen et al., 2008)	TES	37	150	256	HWP/Scan
Keck Array(Nguyen et al., 2008)	TES	55/37/26	100/150/220	288/512/512	HWP/Scan
MBI(Korotkov et al., 2006)	NTD	60	100	4	Int.
Poincare(Chuss, 2008)	TES	84/30/24	40/90/150	36/300/60	VPM
PolarBeaR(Lee et al., 2008)	TES	7/3.5/2.4	90/150/220	637	HWP
QUIET I(Samtleben, 2008)	MMIC	20/10	44/90	$\sim$100/1000	ϕ-switch
SPTpol(Ruhl et al., 2004)	TES	1.5/1.2/1.1	90/150/225	$\sim$ 1000	Scan
European-led ground-based:					
BRAIN(Polenta et al., 2007)	TES	60	90/150	256/512	Int.
C_ℓOVER(Piccirillo et al., 2008)	TES	7.5/5.5/5.5	97/150/225	3x96	HWP
QUIJOTE(Rubino-Martin et al., 2008)	HEMT	54-24	10-30	34	HWP

Notes: Abbreviations in the modulator column are for halfwave plates (HWP), pure scanning (Scan), scanning with stepped HWP (HWP/Scan), variable-delay polarization modulators (VPM), waveguide phase switch (ϕ-switch) and interferometers (Int.); experiments with no hardware polarization modulator are indicated by a dash, and will reconstruct polarization via their scan modulation only.

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